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THE LONGITUDINAL PROFILES OF GLACIATED VALLEYS

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ABSTRACT

Steps in the longitudinal profiles of valleys and reversals of the general downvalley slopes frequently associated with the steps are characteristic features of glaciated troughs, and the origin of stepped profiles presents some unsolved problems.

Some steps are rather obviously related to structures of the underlying rock, but in other cases such a relation is very doubtful. Whether controlled by rock structures or not, steps are explained according to one hypothesis as closely related to preglacial valley constrictions. In contrast with this view, however, is an explanation which connects breaks of slope with expansions of the glacier channel necessitated by accessions of volume in the ice stream, where it was augmented by the junction of tributaries. This hypothesis is particularly applicable to some prominent steps near the heads of troughs which have been fed with ice from expanded catchment areas.

Other hypotheses relate step development to subglacial sapping and to processes associated with cirque-wall sapping.

INTRODUCTION

In longitudinal profile, glacial trough floors are notoriously uneven. Not only are there many steep descents in them, irregularly spaced, but another feature commonly found is reversal of slope on the rock-floor. Thus are formed the rock basins that contain many postglacial lakes in upper valleys of alpine regions. This note is a discussion of some hypotheses to account for such features of the bedrock profiles of upper valleys; it is not concerned with the basins of moraine-dammed lakes nor with piedmont lakes in lower valleys, the origin of which has ceased to be a controversial matter.

The only glacial valleys that now have smoothly graded floor profiles are those which have been graded up by valley filling of postglacial date, such, for example, as the great eastern valleys of the New Zealand Alps. Aggradation of this kind is inevitable eventually in all the strictly overdeepened parts of a glacial trough and is effected rapidly where large glaciers remain and are efficiently eroding in upper valleys, supplying abundant debris to be built into "valley trains," or lower-valley aggraded plains, and indeed in every case where vigorous erosion is still in progress in valley-head regions. Beneath the thick alluvial gravels of aggraded plains, which may bury trough floors to a great depth, it may be that these rock-floors are as irregular in profile as those of other valleys which are not hidden.

Irregularity of longitudinal profile beneath glaciers is a condition to be expected. Some such irregularity is no doubt homologous with that found in stream-cut valleys that are not yet graded. Ice falls, which are common features of present-day glaciers, may have been present at steep and as yet "ungraded" parts of glacier-trough floors even at the height of an ice flood. In addition, however, to such possible irregularities, it is reasonable to explain a great many, perhaps most, of the breaks of slope of rock-floor profiles as an expression of the relatively minor unevennesses of the floor beneath a thick ice stream with a graded upper surface.

Differential excavation by glaciers still ungraded is the kernel of the explanation of trough forms adopted by De Martonne, whereas some other authors hold that surfaces of the vanished glaciers had more even gradients than the now-exposed floors of their channels.

The explanation of basin-like expansions alternating with contractions of the trough width cannot be separated from that of breaks in the longitudinal profile. Many basins are not only lateral expansions of the valley form but are also hollow floored—being walled in on the downvalley side by rock bars (or riegels)—and either still contain lakes (especially in upper valleys) or have contained lakes which have been destroyed by alluvial filling and the cutting of very young postglacial ravines through the impounding riegels. The relation of hanging side-valleys to the main must also be taken into consideration.

THE GLACIAL STAIRWAY

The successive descents in the valley profile may be described as steps. At each step is a more or less well-developed riegel (Figs. 1

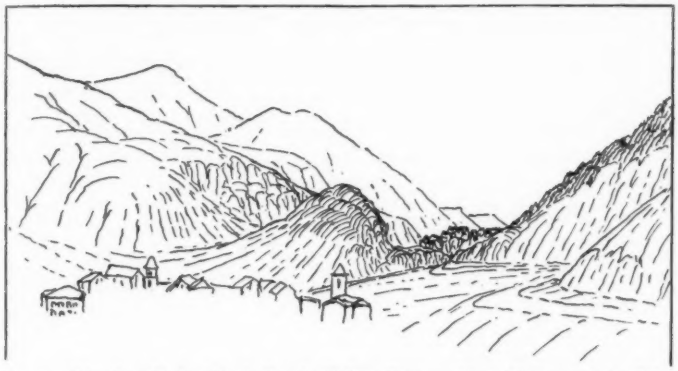

FIG. 1.—Riegel at Bivio, Oberhalbstein Valley, Eastern Alps. Photograph by Sölch

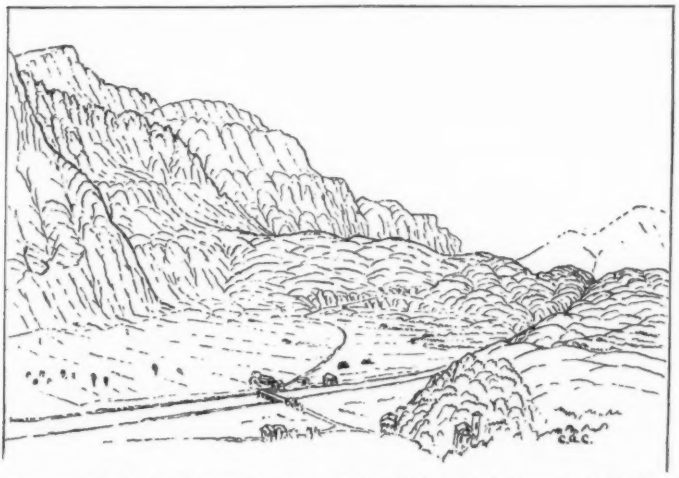

FIG. 2.—The basin at Innertkirchen and the Kirchet riegel, through which is cut the deep and narrow postglacial gorge of the Aar, Switzerland.

and 2), and the tread of each step may be hollowed to the concave profile of a rock-basin lake. In plan, apart from features of the floor,

there may or may not be some constriction of the trough at a riegel, but De Martonne considers that alternation of narrower troughs at riegels with broadly expanded basins is a typical feature of glacial valleys.[1] If the step-tread basins are occupied by lakes, as is often the case, especially as valley heads are approached, these may follow one another like beads upon a string—paternoster lakes.[2] Though some of the lakes thus strung out along valley floors are held up by morainic dams, others are separated by rock bars and mark successive steps (Fig. 3). The stairway is steep at the valley

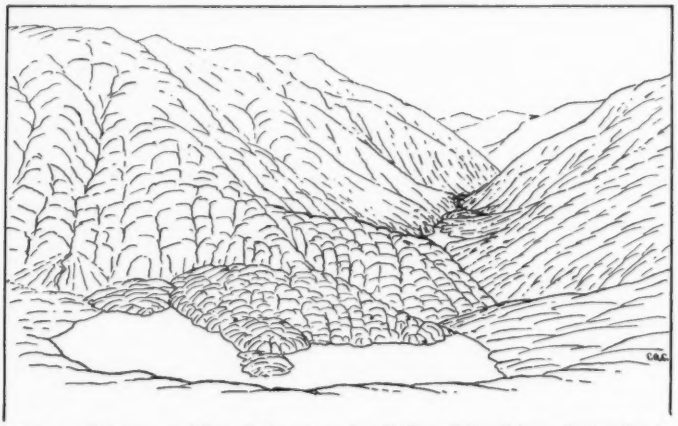

FIG. 3.—Paternoster lakes of the upper Aar Valley, Grimsel Pass, Switzerland

head but may continue with diminishing gradient downvalley for many miles.

Hypotheses current for the explanation of riegels and steps may be classed in two categories: those which relate them to rock structures and those which do not. It is quite probable that different explanations fit different cases, forms of somewhat different origin having as a common characteristic the strong contrast they present to the normal features of normal (river-cut) valleys.[3] Some observers

[1] E. de Martonne, *Traité de géographie physique* (5th ed., 1935), Fig. 348.

[2] F. Nussbaum, "Die Täler der Schweizeralpen," *Wiss. M. schweiz. Alp. Mus. Bern*, Vol. III (1910).

[3] Notwithstanding the contrary opinion of E. de Martonne on this point. "Quelques données nouvelles sur la jeunesse du relief préglaciaire dans les Alpes," *Rec. de trav. Cvijić* (Belgrade, 1924), p. 125.

have noted a frequent relation of riegels in the Alps to bars of limestone formations which appear to have offered considerable resistance to erosion. On this hypothesis one must regard the rock barriers as having probably retarded preglacial normal erosion as well as glacial erosion, and the riegel, though not actually a feature inherited from the preglacial valley, may be situated at a preglacial valley constriction and may be in part the rubbed-down roots of former valley-side spurs at such a point.

Those who explain the trough form of the glacier channel as developed mainly by vertical glacial corrasion and derive the glaciated forms from somewhat widely opened, mature preglacial valleys must, however, regard riegels (if they are related to outcrops of resistant rock) as features that have made their appearance owing to glacial vertical corrasion being slower on the hard-rock bars than elsewhere. Such riegels are thus possibly features of valley youth in the glacial cycle—features that must disappear again if the glacier remains in existence sufficiently long to rub them down.

HYPOTHESIS OF PREGLACIAL CONSTRICTIONS

According to the view of De Martonne, which he has vigorously advocated,[4] any narrowing of the preglacial valley—in some instances due to causes other than the presence of transverse hard-rock barriers—may determine the position of a riegel. The origin of the narrows might be superposition, or antecedence, or a local rejuvenation due to a capture or development of a cutoff in the course of a river. Most often, however, valley constrictions are related to the rock structure, especially where rivers have been rejuvenated; and strong preglacial rejuvenation is a condition which De Martonne maintains must be postulated in explanation of the occurrence of riegels in glaciated valleys. This he explains as the result of end-of-Tertiary upheavals which have continued and have caused repeated rejuvenations during successive interglacial epochs of normal erosion.[5] He has supported his contention by describing valley forms of the same type—i.e., a succession of more open, graded reaches sepa-

[4] *Ibid.*

[5] "L'Erosion glaciaire et la formation des vallées alpines" (second article), *Ann. de géog.*, Vol. XX (1911), pp. 1–29.

rated by ungraded gorges—in the unglaciated parts of the Var Valley system in the Maritime Alps.[6]

It is an essential part of De Martonne's theory that the glacial modification of form which preglacial valleys have undergone consists in the main of widening, accompanied by a moderate amount of deepening in the basins, but very little deepening on the riegels, and practically no erosion on the fronts (risers) of the steps. These arguments are applicable particularly in explanation of the forms in regions of moderate glaciation, where it is apparent there has been little vertical corrasion. Thus in the less heavily glaciated valleys on the eastern side of the New Zealand Alps, as also in the upper Vésubie Valley, in the Maritime Alps, described by De Martonne, there is a marked absence of alternating riegels and basins, and hanging valleys do not occur (with the exception, in the New Zealand valleys, of those developed from high-level cirques by headward cirque-wall sapping);[7] and it can be urged that the rocks of the terrain are not very resistant and afford no marked alternations of relatively weak and resistant formations. Even in the more heavily glaciated districts of southwestern New Zealand, where again there are no marked alternations of weak and resistant rocks but where very deep wall-sided troughs occur, there are indeed hanging valleys at great heights, which vouch for deep-trough excavation; but valley constrictions and typical basin-and-riegel alternation on a scale comparable with the grand scale of the troughs are quite rare. Gilbert has not found features of this kind in Alaska, where great irregularities noted in the depths of fiords seem not to be systematically arranged in steps.[8]

The occurrence of the basin-and-riegel type of valley seems to be confined to certain regions and to be related to rock structure rather than to anything else. Its presence in the Tinée and its absence from the upper Vésubie, of the Var Valley system in the Maritime Alps,[9]

[6] "Quelques données nouvelles sur la jeunesse du relief préglaciaire dans les Alpes," *op. cit.*

[7] R. Speight, "Note on the Hanging Valleys of the Upper Rangitata Valley," *Trans. N.Z. Inst.*, Vol LIV (1923), pp. 90–98.

[8] G. K. Gilbert, "Alaska," *Harriman Alaska Expedition* (1903), Vol. III, p. 159.

[9] De Martonne, "Quelques données nouvelles sur la jeunesse du relief préglaciaire dans les Alpes," *op. cit.*, p. 133.

must be a result of the structure rather than of the presence or absence of rejuvenated preglacial valley forms. This is an outcome of De Martonne's arguments, though it cannot be doubted that where an alternation of gorges and graded reaches is already present rejuvenation will develop features which require but slight modification to become riegels and basins. A test of this hypothesis as applied to the explanation of any particular landscape will be that discordance of valley junctions will be small except in those cases where the discordance can be explained as in part preglacial.

The proponents of the theory of overdeepening, to use the term in a rather unrestricted sense, explain most riegels as bars of rock either obviously more resistant than the enclosing formations or presenting specific resistance to a particular kind of erosion (in this case glacial abrasion), owing to absence of close jointing or perhaps to some less obvious property of the rock.[10] These rock bars were in the course of reduction up to the time of the disappearance of the ice, but as long as excavation continued on the more easily yielding rocks up and down the valley from them, they stood out as riegels. Only if a limit—some kind of base-level controlling valley depth—could be reached, then might the riegels be worn down and disappear.[11]

The problem of steps is not quite the same as that of riegels, though commonly a riegel is present at the brink of a step. Some which are related to cross-valley bars of hard rock determine steps, for the ice stream passing over a riegel bar will excavate more deeply on the weaker rocks beyond it.

De Martonne ascribes glacial erosion both vertical and lateral to

[10] "The variations of structural resistance or firmness that the searching pressure and friction of a heavy glacier could detect might be hardly recognizable to our superficial observations" (W. M. Davis, "Glacial Erosion in France, Switzerland, and Norway," *Geographical Essays* [1909], p. 662).

[11] It seems impossible to agree entirely with W. M. Davis, who went much further than this and believed he recognized complete homology between "broken-bedded" glacial channels and the ungraded steep courses of young rivers. "The reaches on the weaker or more jointed rocks may be eroded during youth to a somewhat greater depth than the sill of more resistant or less-jointed rock next downstream. . . . . If the glaciers had endured longer in channels of this kind, the 'rapids' and other inequalities by which the bed may be interrupted must have been worn back and lowered, and in time destroyed (*ibid.*).

corrasion by the ice stream,[12] which tends to develop for itself in easily eroded material a channel whose cross section is an arc of a circle. "It is above all by its weight that the glacier does its work."[13] Erosion, measured by friction between the glacier and its bedrock floor varies, he argues, as the cube of the thickness of the ice and as the cosine of the angle of slope of the ice surface.[14] Erosion must be of small value, therefore, on a step (riser) or on the steep downvalley slope of a riegel.

Though corrasion may be weak on step fronts, there is a possibility which, though not considered by De Martonne, ought not to be ignored. It is that more or less vigorous sapping similar to *bergschrund* sapping of cirque walls will take place on step fronts, but closely similar conditions will prevail only if the glacier descends as an ice fall over the step and is broken by crevasses that extend to the rock-floor. In the case of thick glaciers, this does not seem possible,[15] but where thin glaciers descend steps as ice falls it seems highly probable that the step fronts, though protected by their steep slopes from active corrasion, are receding at an appreciable rate as a result of sapping. De Martonne believes in the existence of ground crevasses in full-bodied glaciers,[16] as did Hess until 1929, but does not attribute any importance to a subglacial sapping process as a possible cause of headward retreat of steps. He regards the steps, on the contrary, as remaining fixed in position, whether related to bars of hard rock or not.

Another subglacial erosive process which must not be ignored is plucking,[17] of which there is evidence on the downvalley slopes of some steps and riegels and of the various knobs and prominences that have been overswept by ice (*roches moutonnées*). The ice freezes

[12] De Martonne's "sapement" is lateral corrasion, not "sapping," as understood by Willard Johnson.

[13] "Quelques données nouvelles sur la jeunesse du relief préglaciaire dans les Alpes," *op. cit.*, pp. 135–36.

[14] *Ibid.*

[15] H. Hess, "Das Eis der Erde," *Handbuch d. Geophysik*, Vol. VII, No. 1 (1933), p. 58.

[16] De Martonne, *Traité de géographie physique*, Fig. 334.

[17] Recognized by most glacial erosionists. See especially Willard D. Johnson, "The Profile of Maturity in Alpine Glacial Erosion," *Jour. Geol.*, Vol. XII (1904), p. 574; and T. C. and R. T. Chamberlin, "Certain Phases of Glacial Erosion," *Jour. Geol.*, Vol. XIX (1911), pp. 193–216.

to loosely held joint-bounded blocks of rock (water passing readily into ice at the freezing temperature wherever tension is developed), and the blocks are dragged away, and even rock that is free from cracks or flaws may be torn apart in some cases.[18] The adhesion of ice to rock under a glacier will vary, according to De Martonne,[19] inversely as the tangent of the slope of the ice surface, but the field evidence that plucking has occurred where the rock-floor slopes steeply downvalley is incontrovertible. The effects of abrasion (generally termed "scour" when contrasted with "pluck") being in such circumstances at a minimum, it may be that here a very moderate amount of plucking has left a visible result, whereas the results of more efficient plucking on other surfaces have been obliterated by powerful scour. Except under thin glaciers (where sapping of steps may occur), the riegel, or the step without a riegel, may perhaps, therefore, be a very stable form scarcely subject to attack from the downvalley side.

The contention of De Martonne that preglacial-stream erosion has been responsible for the production of the initial forms of basins and riegels, the work of glaciers adding only the finishing touches, has been supported by Sölch,[20] who, however, goes farther and enlists the support of English and French advocates of glacial protection and of erosion by subglacial streams. He quotes with approval phrases applied by Harker to glacial features in Skye, such as that ice work had given "final touches" to the forms and had been responsible only for "actual details." The more recent description of the glaciated hills of Skye given by Lewis,[21] however, suggests that such phrases in descriptions written forty years ago were more often than not introduced as concessions to the then prevailing mood of extreme caution and skepticism regarding any theory of deep glacial erosion.

The theory of preglacial origin of steps implies that most of them occur either in heterogeneous terrains at the points where the more

[18] O. D. von Engeln, "Palisade Glacier," *Bull. Geol. Soc. Amer.*, Vol. XLIV (1933), p. 594.

[19] "Quelques données nouvelles sur la jeunesse du relief préglaciaire dans les Alpes," *op. cit.*, p. 136.

[20] J. Sölch, "Flusse- und Eiswerk in den Alpen," *Pet. Mitt. Ergänz.*, Nos. 219, 220 (1935).

[21] W. V. Lewis, "A Melt-Water Hypothesis of Cirque Formation," *Geol. Mag.*, Vol. LXXV (1938), pp. 249–65.

resistant members have held up preglacial rivers in ungraded gorges or in localities where successive rejuvenation nicks have been following one another up the valleys of preglacial rivers. The latter alternative is favored by Sölch.

HYPOTHESIS OF OVERDEEPENING

The hypothesis of overdeepening, as applied to the origin of steps and of riegel-and-basin valley forms, has been advocated especially by Penck[22] but has been consistently favored also by Davis in his many descriptions of glaciated features. Gilbert, though a believer in the power of an ice stream to make deep excavations,[23] did not make specific application of the theory of vertical corrasion to this particular problem, as far as I am aware.

The overdeepening hypothesis attempts to explain some riegels (and necessarily the steps associated with these) as fixed in position and thus somewhat stable features in the glacial cycle, in that they are rooted on hard-rock bars. Most steps are considered stable forms by the advocates of the hypothesis, however, for a different reason. A cascading or stepped glacier-surface profile, regarded by De Martonne as stable, is in reality an ephemeral form of youth, or, where found, as it very commonly is, in the shrunken glaciers of the present day, gives no indication of what glacier surfaces were as they existed at the height of an ice flood, to which it is assumed that floor profiles were adjusted. Steps in the rock-floor, therefore, are necessary elements of the profile of maturity beneath glaciers with graded-surface slopes, just as a step down to the main floor from the mouth of a hanging valley exists normally beneath glaciers with accordant junctions.

This principle is embodied in Penck's "law of adjusted cross-sections,"[24] which is applicable to streams whether of ice or water. "If there is no sudden change in the velocity of the moving bodies—those changes will always disappear in the course of time—or in the precipitation and evaporation or ablation of a certain region, the

[22] A. Penck, "Die Uebertiefung der Alpentäler," *Verh. VII Internat. Geog. Kongr.*, 1900, pp. 232–40; "Glacial Features in the Surface of the Alps," *Jour. Geol.*, Vol. XIII (1905), pp. 1–17.

[23] Gilbert, "Glaciers," *op. cit.*

[24] "Glacial Features in the Surface of the Alps," *op. cit.*

neighboring cross-sections will increase in the same way as the areas do."[25] In conjunction with the circumstance that glacial erosion is "selective," i.e., governed to some extent by the nature of the rocks of the terrain, the law of cross sections may account for the variation of transverse profile from a broad and shallow to a narrow and deep form where a rock boundary is crossed. Thus "many steps in glacial valleys are caused by highly resistant rocks."[26]

Confluence of secondary glaciers and diffluence, where distributary glaciers leave the main, are responsible, however, for abrupt accessions and diminutions of volume, enlargements, and shrinkages of the cross section of the glacier; and at such points the cross-section law requires generally a deepening or shallowing of the main trough. The latter is important in connection with the theory of the origin of lake basins, while abrupt deepening, forming "steps of confluence," has expression not only in the hanging mouth of a side valley but also in a step in the floor of a main valley, more or less pronounced according to the ratio of the sections of tributary and main and the opportunity the trunk glacier may have had to increase its section by widening as well as deepening below the confluence.

CONVERGENT CIRQUES AND THE TROUGH-END

The law of adjusted cross sections does not very satisfactorily explain all the peculiar features of glaciated valleys; the alternation of riegel and basin seems most often related to structure, and some other explanation may have to be found for steep stairways near the heads of some valleys. A single, very pronounced step in the upper valley, however, which is regarded by Penck as marking the end of the trough or channel occupied by the glacier tongue, finds a most credible explanation in the cross-section theory. This feature, by no means universally present, though considered by Penck as one of the characteristic features of glaciated mountain regions, is found fully and typically developed where a valley glacier is fed at the head with firn from a cluster of converging cirques so that it has a broadly expanded head névé. The name applied to the imposing trough-head step by Penck[27] is "trough's end," for which one might substitute "trough-end" or von Engeln's[28] term "cross wall." It cannot be doubted that an imposing trough-end cliff exists beneath the Franz

[25] *Ibid.* [26] *Ibid.* [27] *Ibid.*, p. 2. [28] *Op. cit.*, pp. 575–600.

Josef glacier at the point where the ice from its broad névé fields is gathered into a narrow stream (Fig. 4). A trough-end in a deeply

FIG. 4.—Head of the Franz Josef glacier, New Zealand. Photograph by V. C. Browne, Christchurch.

excavated Swiss glacial valley is shown in Figure 5. Probably the best published diagram in illustration of converging cirques at a valley head, the confluent ice from which has been concentrated in a

narrower and necessarily deeper channel at a trough-end, is W. M. Davis's Figure 156 in his *Erklärende Beschreibung der Landformen* (1912).

At such a constriction, which may be assumed to have been preglacial, at least in part, "in order to maintain a continuous movement an increase of velocity was necessary. . . . . This increased velocity must act on the bed of the glaciers until a sufficient depth is

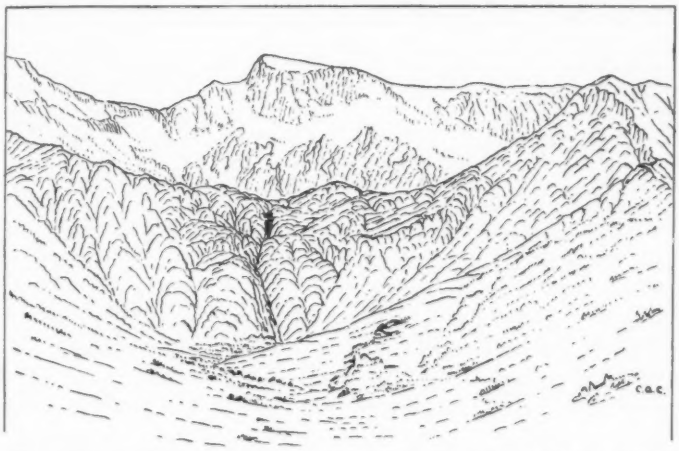

FIG. 5.—Step, or trough-end, 1500 feet high, separating the head of the Adelboden trough (Switzerland) from the valley-head cirque above it.

attained. Theoretically this depth must be 57 per cent (that is, $\frac{\pi}{2} - 1$) greater than that at the semicircle from which the glaciers came."[29]

This theory, that typical trough-ends are related to glacial confluence, seems preferable to that of De Martonne, which relates them to rejuvenation nicks in preglacial-stream profiles little modified by glacial erosion. On the latter theory, though the preglacial longitudinal profile might be regarded as but little modified, very great lateral enlargement of the head of the trough must be assumed immediately below the step, sufficient to convert a postulated preglacial, narrow ravine head into a great amphitheater. Such a form is found, indeed, immediately below most valley steps and riegels,

[29] Penck, "Glacial Features in the Surface of the Alps," *op. cit.*, p. 9.

where the valley has been broadly opened out to a trough or U-form closely simulating that just above the step, which, according to De Martonne's theory, is that of a more wide-open reach of the preglacial valley only slightly modified.

HYPOTHESIS OF SUBGLACIAL SAPPING

As noted previously, it seems scarcely possible that ground crevasses can exist in thick glaciers or that vigorous subglacial sapping such as might be related to freeze-and-thaw effects under open crevasses can have contributed appreciably to step development under such glaciers. Under thin glaciers, especially toward valley heads, where presumably preglacial gradients were steep and infantile glaciers had broken surfaces, quite possibly conditions favored development of steps by sapping, which would cause headward retreat and accentuation of initial declivities analogous to the development of autogenetic[30] falls by plungepool back-scour in the valleys of young rivers. This process, in combination with some corrasion on the treads of steps, may be sufficient to account for the characteristic strings of paternoster lakes toward some glacial valley heads. The cause for such local overdeepening, which is of more general occurrence than the alternating basin-and-riegel form in lower valleys and is found where the rocks of the terrain are of uniform character according to ordinary standards, must be sought in differences in the joint pattern or something else in the texture of the rocks influencing the selective power of glacial corrasion.[31] Even the large-scale features of the Yosemite Canyon are attributed by Matthes[32] to alternate absence and presence of abundant joints in different parts of a granite terrain. By-products of this theory, however, are (1) that efficiency of glacial corrasion depends almost entirely on a glacier's ability to pluck, and (2) that steps are rooted on the structure and are thus not free to migrate upvalley.

[30] W. M. Davis, *Bull. Geol. Soc. Amer.*, Vol. XLIII (1932), p. 438.

[31] According to an early theory put forward by De Martonne (which he regarded afterwards as secondary or alternative to his preferred theory of mechanical corrasion controlled by initial slopes), upper-valley steps (or steps in a cirque stairway) mark the positions of glacier terminals during halts in a retreat, or their positions in successive glacial epochs, and basins have been hollowed out under thicker parts not far behind rather steep glacier snouts during each halt ("L'Erosion glaciaire et la formation ...," *op. cit.* [1910], p. 313).

[32] F. E. Matthes, "Geologic History of the Yosemite Valley," *U.S. Geol. Surv., Prof. Paper, 160* (1930).

The hypothesis of autogenetic step development by accentuation of small initial breaks of slope has been worded as follows by T. C. and R. T. Chamberlin:

> If a pre-existent step or down-set crosses the bottom of the valley at any point beneath a glacier, or if a step is developed by structural inequalities, and if the down-set is sufficiently great in proportion to the thickness of the ice to cause effective crevassing through the whole depth of the glacier, the conditions at the base of the step are not radically different from those at the base of the cirque wall, for there is in effect a break in the continuity of the motion of the glacier, and the beginning of a new motion in the ice mass below. The rock face of the step may be regarded as a cirque wall in a modified sense. From it masses may be detached and, falling against the ice wall, become attached and dragged forward. . . . . Sapping and stoping seem to be rather general phenomena of the basal action of glaciers. The operation of the stoping process at several points in a long glacier tongue, by developing successive ice falls between more or less level stretches, results in a rude stairway of giant tread.[33]

Although starting with the same premise of initial inequalities of profile, this hypothesis is radically different from that of De Martonne, for steps developed by sapping are not stationary but must continue to retreat upvalley as long as sapping is active. Steps originating thus, and probably increasing in height so as to become very conspicuous landscape forms if the glacier covering them melts away soon enough, must, however, be ephemeral features of the trough profile under continuous glaciation and must eventually be merged into the wall of the valley-head cirque, into the trough-end, or into the wall of some other step controlled in a mature profile by ice-stream cross sections, according to Penck's theory. Troughs that do not receive tributaries (do not branch) must develop stepless floors like that which may be present under the Galiano Glacier in Alaska,[34] and like that possibly present beneath alluvial filling in the Clinton Canyon in New Zealand, but the glacier in the latter must have been thousands of feet deep, much too deep for ground crevasses.

HYPOTHESIS OF HEADWARD GLACIAL EROSION

Yet another hypothesis emerges as a corollary of the theory of headward glacial erosion advocated especially by Johnson[35] and by Taylor.[36] Johnson credited sapping with a great deal more than the

[33] *Op. cit.*, pp. 213–14. [34] Von Engeln, *op. cit.*, p. 595. [35] *Op. cit.*, pp. 569–78.

[36] Griffith Taylor, "Physiography and Glacial Geology of East Antarctica," *Geog. Jour.*, Vol. XLIV (1914), pp. 365–82, 452–67, 553–71.

development of the imposing back walls of cirques. According to his view, in some cases during the development of a high valley-head wall by the sapping process, the head wall "breaks back into steps successively shortening in length of tread. The rearward steps may continue to be marked by schrunds rising to the glacier surface; living glaciers in fact are often characterised by 'cascades' in their upper courses."[37]

This implies that not only the valley-head cirque but the glacial trough also (or a part of it at least) has been developed by headward erosion, and step-making is incidental to this process. Those steps (earliest formed) which remain farthest downvalley under the glacier, being no longer so vigorously sapped, become less sharply defined under the "dulling influence of scour."

The "palimpsest" theory of Taylor[38] is a variant of Johnson's hypothesis, in which he supposes a stairway of cirques to have been developed by isolated glaciers and afterwards modified by a stream of continuous ice. This has rounded off the rock bars between cirques, converting them into typical riegels and steps. So he explains the great Nussbaum riegel in Antarctica.

It is a part of Johnson's hypothesis that at least the later formed steps, though outpaced by rapidly sapped valley-head cirque walls, may still be migrating headward. It is noteworthy, however, that the migration of steps progressively abandoned by the glacier as valley heads, as its head wall "breaks back" with development of ever newer cirques in a continuous stairway, implies the reverse of von Engeln's idea of steps following one another in upvalley retreat until they are eliminated from the profile, even though he admits that a stern chase is a long one.[39]

Johnson's hypothesis has this advantage over the Chamberlin–von Engeln hypothesis of subglacial sapping in that it does not have to postulate in regions like the High Sierra of California the existence of distinctly nicked stream profiles in the preglacial epoch. On the other hand, it rules out the possibility—probability, indeed—that some, if not most, stepped glacial troughs are developed from stream valleys by processes of glacial erosion in which abrasion and some form of subglacial sapping both may take part.

[37] *Op. cit.*, p. 575. [38] *Op. cit.* [39] *Op. cit.*, p. 595.

NOMENCLATURE AND CORRELATION OF APPALACHIAN EROSION SURFACES

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ABSTRACT

The erosion surfaces of eastern Pennsylvania and adjacent areas are analyzed, and a correlation with the erosion surfaces of western Pennsylvania, eastern Ohio, eastern Kentucky, and southern New York is proposed. Three erosion surfaces and an extensive strath are found in both the eastern and the western areas. The Upland surface, common to both regions, is the only true peneplain. The younger erosion surfaces and the straths are correlated by their position below the Upland surface. The age of the surfaces is considered.

INTRODUCTION

A review of the literature dealing with the erosion surfaces of eastern Pennsylvania and adjacent areas illustrates the multiplicity of concepts which various workers have had of the development, extent, and number of surfaces present. Although the first exact study of these surfaces proposed the modest number of two, i.e., the Schooley and Somerville,[1] later studies have run the gamut from one[2] to twenty-four.[3]

That this diversity of opinion should exist is not surprising. Field studies and analysis of projected profiles show various elevations which may be grouped to suggest individual surfaces at numerous positions. As the geologic structure is complex and a wide variation in resistance to erosion occurs in the formations underlying this area, the interpretation and correlation of the apparent surfaces is extremely confusing.

Although numerous concepts have been presented, they may be divided into three schools of thought, as K. Bryan, A. B. Cleaves,

[1] W. M. Davis and J. W. Wood, Jr., "The Geographic Development of Northern New Jersey," *Proc. Boston Soc. Nat. Hist.*, Vol. XXIV (1890), pp. 365–423.

[2] G. H. Ashley, "Studies in Appalachian Mountain Sculpture," *Bull. Geol. Soc. Amer.*, Vol. XLVI (1935), pp. 1395–1436.

[3] W. O. Hickock, "Erosion Surfaces in South-central Pennsylvania," *Amer. Jour. Sci.*, Vol. XXV (1933), pp. 101–22.

and H. T. U. Smith[4] have stated in their excellent summary of the Appalachian erosion-surface problem. First, there is the initial interpretation of Davis and Campbell of not more than three surfaces; second, the viewpoint of Barrell and workers presenting his concept of multiple surfaces; third, a recent group, influenced by Johnson and Ver Steeg, who reduce the number of surfaces. Of this last group, Ashley is the most extreme proponent of reduction, as he conceives of only one surface.

For several years the writer has been studying the erosion surfaces in the northern portion of the Appalachian plateaus from central New York to northern Kentucky. The results of these studies have been incorporated in a series of four articles.[5] In the initial article, a correlation was proposed between the surfaces west of the Allegheny Front with those to the east. A review of that correlation and a more detailed presentation of the facts upon which it was based is desirable at this time.

EROSION SURFACES OF THE NORTHERN APPALACHIAN PLATEAUS

The Appalachian plateaus are better suited for initial studies of erosion surfaces than are the Valley and Ridge, Blue Ridge, or Piedmont provinces, as the geologic structure is relatively simple. With gently dipping beds, the greatest variable which must be considered is the resistance of the various formations to erosion. In steeply dipping and faulted strata numerous variables are introduced, such as thickening of resistant beds at the apexes of plunging anticlines and synclines and the rapid alternation of resistant and weak beds in short horizontal distances. In addition, the folding brings the same formations to the surface at greatly different elevations and locations.

Field studies and analysis of selected projected profiles show the presence of three erosion surfaces and one strath in the Appalachian

[4] "The Present Status of the Appalachian Problem," *Zeit. für Geomorphologie*, Band VII, Heft 6 (1933), S. 312–20.

[5] W. S. Cole, "Identification of Erosion Surfaces in Eastern and Southern Ohio," *Jour. Geol.*, Vol. XLII (1934), pp. 285–94; "Rock Resistance and Peneplain Expression," *ibid.*, Vol. XLIII (1935), pp. 1049–62; "Development and Structural Control of Erosion Surfaces," *ibid.*, Vol. XLV (1937), pp. 141–57; "Erosion Surfaces of Western and Central New York," *ibid.*, Vol. XLVI (1938), pp. 191–206.

plateaus in the area studied. In order from oldest to youngest these are: (1) Upland, (2) Allegheny, (3) Lexington, and (4) Parker strath. This classification was proposed by the writer in 1934, although at that time the Upland peneplain was referred to as the Kittatinny. In subsequent articles additional data were presented to substantiate the initial classification.

N. M. Fenneman[6] proposes a fourfold classification of erosion surfaces as well as certain subsequent views of the writer, although no reference is made to the writer's articles. Fenneman uses the names Schooley, Allegheny, Worthington (Lexington), and Parker strath.

K. Ver Steeg[7] maintains that there are only two erosion surfaces and a strath in the Appalachian plateaus, although he revises his correlation. In 1931[8] he stated that the Lexington surface of Ohio and Kentucky is the equivalent of the Somerville strath of New Jersey. The writer (1934)[9] advanced arguments to show that this correlation could not be maintained. In a recent article Ver Steeg (1940) admits the writer's contention that the Parker strath is the time equivalent of the Somerville strath.

But Ver Steeg is not willing to separate the Allegheny and Lexington erosion surfaces.[10] The writer has offered what he believes to be convincing proof in the form of projected profiles in former articles that the Allegheny and Lexington erosion surfaces are separate and distinct. These arguments need not be repeated here.

In view of the fact that three major surfaces and a well-developed strath stage are recognized in the Appalachian plateaus west of the Allegheny Front in the areas studied, it is logical to expect that a similar number of surfaces should be found in the area east of the Allegheny Front in Pennsylvania and adjacent areas, as it is a gen-

[6] *Physiography of Eastern United States* (New York: McGraw-Hill Book Co., 1938), pp. 293–302.

[7] "Correlation of Appalachian Peneplanes," *Pan.-Amer. Geol.*, Vol. LXXIII (1940), pp. 203–10.

[8] "Erosion Surfaces of Eastern Ohio," *ibid.*, Vol. LV (1931), p. 192.

[9] "Identification of Erosion Surfaces in Eastern and Southern Ohio," *op. cit.*, p. 288.

[10] "Correlation of Appalachian Peneplanes," *op. cit.*, p. 209.

erally accepted fact that this area of the Appalachian Highland has had a similar history in later geologic time.

The studies in the Appalachian plateaus have demonstrated convincingly that toward the mouths of the streams the older surfaces have been destroyed. Nearer the headwaters a younger surface fades into an older in a series of straths which extend along the lines of the major streams. The various surfaces may be imagined as a series of gigantic steps descending from the highest or oldest surface on the east to the youngest surface on the west, although it is true that the younger surfaces penetrate all the older as straths, and monadnock areas persist on the younger surfaces in areas of resistant rocks.

In contradistinction to this concept, most of the workers in eastern Pennsylvania have postulated that the older surfaces are recognizable across the hilltops virtually to the present coastline. This is predicated on the visualization of a sloping surface descending regularly from the highest elevations inland toward the coast. The results gained from studies in the Appalachian plateaus as well as in New England by H. A. Meyerhoff and M. Hubbell[11] seem to invalidate this interpretation. It may be argued also that the normal curve of a graded stream is not that of a gently declining convex curve but a steeply concave curve at the headwaters rapidly declining to a gentle slope of very low gradient. The erosion surface developed should follow this stream-curve but with irregularities upon it caused by unequal rock resistance and distance from major drainage lines.

The analysis of the profiles which have been constructed indicates that the Upland surface does not extend over the Valley and Ridge except as monadnocks in the western portion of this province.

THE KITTATINNY-SCHOOLEY PROBLEM

The name Kittatinny was introduced by B. Willis[12] for a restored erosion surface which would truncate the ridge crests of the Valley

[11] "The Erosional Landforms of Eastern and Central Vermont," *Reports Vermont State Geologist* (1927–28), pp. 315–81.

[12] "The Northern Appalachians," *Nat. Geog. Mono. No. 6* (1895), p. 189.

TABLE 1

Davis and Wood (1889)	Keith (1894)	Willis (1895)	Campbell (1903)	Barrell (1920)	Bascom (1921)	Knopf (1924)	Stose (1928)	Fridley (1929)	Ver Steeg (1930)	Hickok (1933)	Cole (This Article)
			Schooley				Kittatinny	Kittatinny	Schooley (Kittatinny)		Upland
	Catoctin	Kittatinny	Harrisburg	Kittatinny	Kittatinny	Kittatinny		Schooley		1,660′	Schooley
										1,520′?	
	Weverton			Schooley		Schooley	Weverton	Mine Ridge		1,450′	
										1,300′–60′	
										1,180′–1,200′	
					Schooley	Mine Ridge				1,040′–1,100′	
										1,000′	
Schooley				Unnamed?						950′	Harrisburg
								Honeybrook		900′	
	Tertiary	Shenandoah		Sunbury	Honeybrook	Honeybrook	Harrisburg (Bryn Mawr)	Sunbury	Harrisburg	800′	
						Sunbury		Harrisburg		700′	
				Harrisburg	Harrisburg	Harrisburg (Bryn Mawr)				660′	
										600′–10′	
										550′	
										500′–10′	
Somerville			Somerville		Early Brandywine (Bryn Mawr)	Lancaster	Brandywine		Somerville	450′	Somerville
										400′+	
					Late Brandywine		Sunderland			360′	

and Ridge province. Workers[13] of the Barrellian school have maintained that the Kittatinny surface was a separate, distinct, and older surface from the Schooley surface of Davis. Ver Steeg,[14] in opposition to these views, has concluded that Kittatinny and Schooley are names given to one surface.

The nomenclature used in several of the most important articles on the erosion surfaces of eastern Pennsylvania and adjacent districts in New Jersey is summarized in Table 1. Exact correlations

TABLE 2

Campbell (1903)	Ver Steeg (1931)	Ver Steeg (1940)	Cole (1934–35–37)	Eastern Pennsylvania (This Article)
Schooley	Schooley (Kittatinny)	Schooley	Kittatinny = Upland	Upland
Harrisburg	Harrisburg	Harrisburg = Lexington (Worthington)	Allegheny	Schooley
Not studied	Lexington (Worthington)*		Lexington	Harrisburg
		Parker strath	Parker strath	Somerville
	Parker strath†			

* The Lexington (Worthington) surface was correlated with the Somerville.

† Parker strath mentioned (Ver Steeg, "Erosion Surfaces of Eastern Ohio," *Pan.-Amer. Geol.*, Vol. LV [1931], p. 185), but not correlated.

of the names used for the various erosion surfaces is impossible, as the various students of this problem have studied in different areas. However, the names are arranged to suggest the probable correlation of the surfaces by the different workers, wherever possible.

Table 2 presents the nomenclature which has been used for western Pennsylvania and eastern Ohio. To this has been added the

[13] G. W. Stose, "A Description of the Delaware Water Gap Sheet," *U.S. Geol. Surv.* (1920); F. Bascom, "Cycles of Erosion in Pennsylvania," *Jour. Geol.*, Vol. XXIX (1921), p. 544; H. M. Fridley, "Identification of Erosion Surfaces in South-central New York," *Jour. Geol.*, Vol. XXXVII (1929), pp. 123–26.

[14] "Wind Gaps and Water Gaps of the Northern Appalachians: Their Characteristics and Significance," *Ann. N.Y. Acad. Sci.*, Vol. XXXII (1930), pp. 89–93.

nomenclature developed in the present article for the surfaces of eastern Pennsylvania.

It is believed that the profiles and the contour map of maximum elevations demonstrate clearly that there is a higher surface in the Appalachian Highlands than the Kittatinny and that the Schooley surface at the type locality is a lowered remnant of the Kittatinny surface.

The Kittatinny surface was extended in the first article by the writer[15] over the higher elevations in Pennsylvania west of the Allegheny Front. In a later article the name Upland[16] was substituted for Kittatinny because of the diverse opinions of the proper use and correlation of the names Kittatinny and Schooley.

Continuous profiles from central Ohio to eastern Pennsylvania (see index map, Fig. 1) seem to demonstrate conclusively that the Kittatinny surface cannot be extended from its type locality across the higher areas west of the Allegheny Front, northwestward to the southern tier of quadrangles in New York or northward into the Catskills. These higher elevations represent a separate, distinct, and older surface below which the Kittatinny was developed and with which it interfingers.

As the Allegheny surface interfingers with the Upland surface from the west a correlation may be established between the Kittatinny surface on the east and the Allegheny surface on the west.

The type locality of the Schooley surface represents a monadnock area above the Harrisburg surface. This monadnock area has been so reduced in elevation that it may not be considered to rise to the elevation of the trace of the dominant erosion surface which bevels the crests of the ridges westward. This fact is shown by the contour map of maximum elevations. Thus the name Schooley is applied to an area which is intermediate between the ridge-crest surface (Kittatinny) and the chief valley surface (Harrisburg).

Logically the name Schooley should be suppressed. However this name has become firmly entrenched in the geologic literature. It may be best to retain the name Schooley and redefine it as the sur-

[15] "Identification of Erosion Surfaces in Eastern and Southern Ohio," *op. cit.*, p. 288.

[16] "Rock Resistance and Peneplain Expression," *op. cit.*, p. 1054.

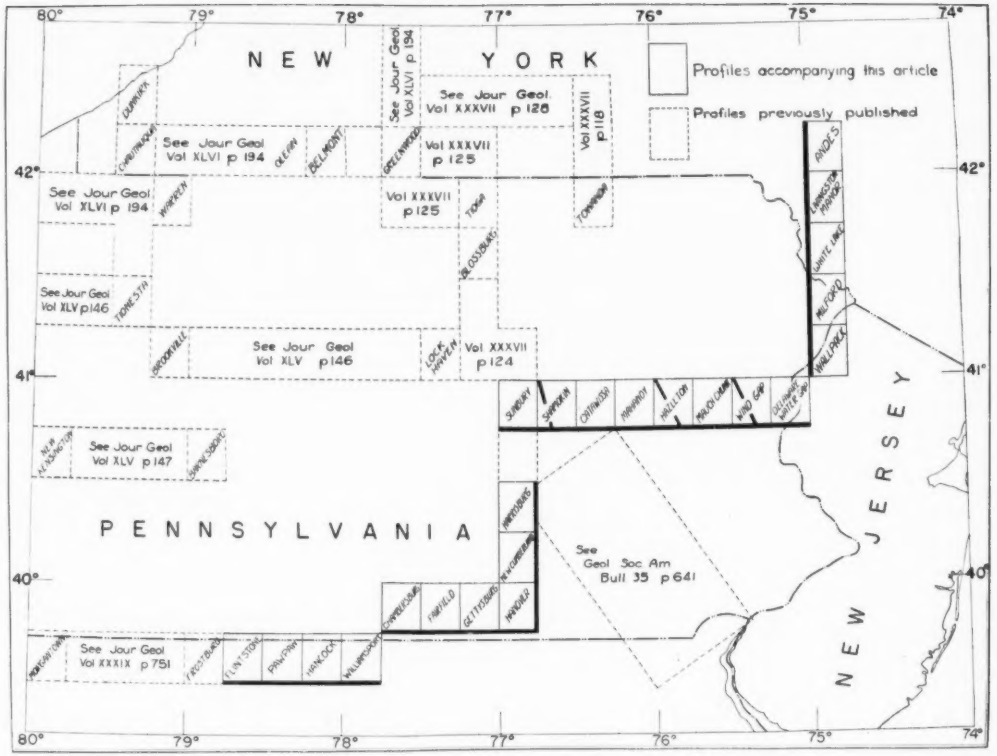

FIG. 1.—Index map. The heavy line in each section indicates the base line

face which bevels the crests of Appalachian ridges. Thus Kittatinny and Schooley represent one and the same surface, as Ver Steeg has maintained. Rather than use the compound name Kittatinny (Schooley), the name Kittatinny will be abandoned in the other sections of this article.

FLINTSTONE-WILLIAMSPORT SECTION

Two surfaces may be recognized on this profile (Fig. 2, *top*). The upper surface is fragmentary, maintained by the crests of the ridges. The average elevation of this surface is approximately 1,900 feet. There is considerable difference in elevation between the highest and the lowest points. If the attitude of the beds is considered in addition to various other factors which govern resistance to erosion, the discrepancies in elevation which are shown by the crests assigned to the upper surface may be appreciated.

The lower surface is illustrated by the low summits of the base line and summits adjacent to it in the background. This surface reaches its maximum perfection in the eastern half of the Williamsport quadrangle, where its average elevation is approximately 500 feet. Westward, this surface rises.

The westward continuation of the Flintstone-Williamsport section has been published by H. M. Fridley and J. P. Nölting, Jr.[17] Their profile illustrates a rapid increase in elevation on the Frostburg quadrangle, which is adjacent to the Flintstone quadrangle on the west. The higher surface at 2,800–3,000 feet extends westward across the Frostburg quadrangle to the Morgantown quadrangle. This surface was correlated by these writers with the Kittatinny. It is the same surface which has been named by the writer[18] the Upland surface. The surface which truncates the crests of the ridges has been correlated with the Weverton erosion surface by Fridley and Nölting.[19] The relationship of the ridge-crest surface to the Upland indicates that the Weverton surface on the east and the Allegheny surface on the west should be correlated. This correlation

[17] "Peneplains of the Appalachian Plateau," *Jour. Geol.*, Vol. XXXIX (1931), p. 751, Fig. 2.

[18] "Rock Resistance and Peneplain Expression," *loc. cit.*

[19] *Op. cit.*, pp. 753–54.

FIG. 1.—Index map. The heavy line in each section indicates the base line

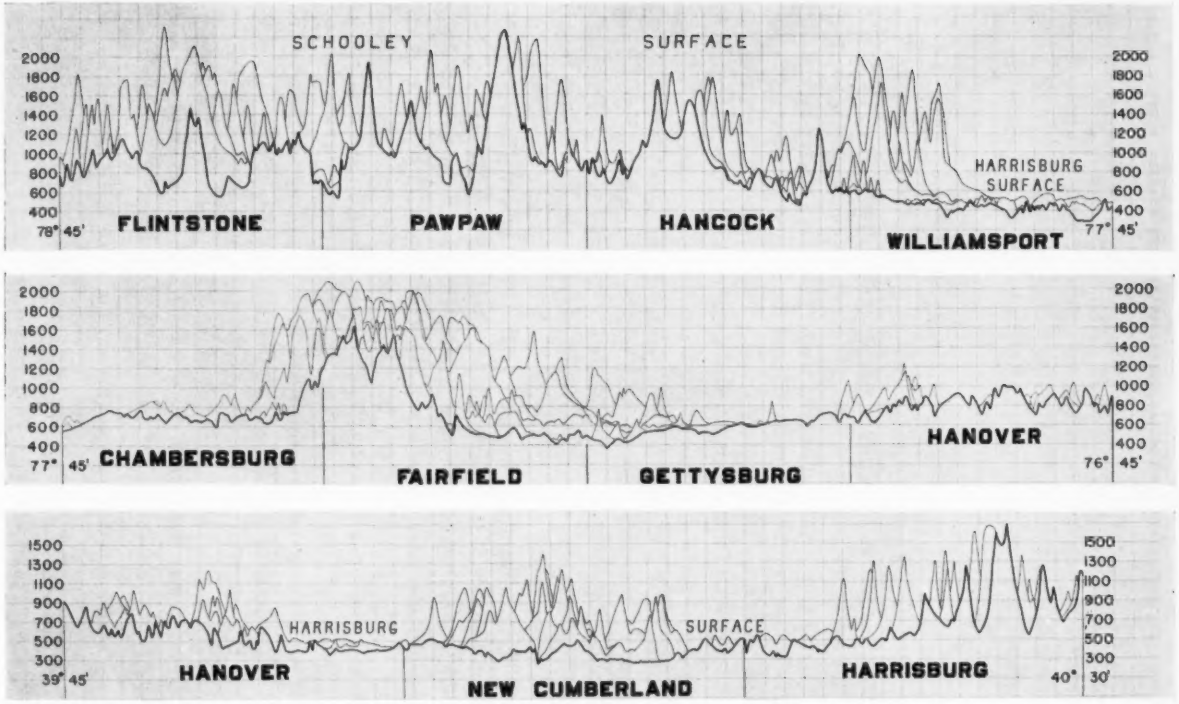

FIG. 2.—*Top:* projected profiles of the Flintstone-Williamsport section. Base line along the southern boundary of the quadrangles. *Center:* projected profiles of the Chambersburg-Hanover section. Base line along the southern boundary of the quadrangles. *Bottom:* projected profiles of the Hanover-Harrisburg section. Base line along the eastern boundary of the quadrangles.

was made by Fridley and Nölting[20] and is substantiated by the present study. Recently Ver Steeg[21] has stated that the Weverton and the Schooley surfaces are one and the same. The present study proves the validity of this correlation.

The lower surface is correlated with the Harrisburg erosion surface. The reasons for this correlation will be given in the discussion which follows. However, it should be noted that the lower surface may be traced from the Williamsport quadrangle to the Chambersburg quadrangle.

projected profiles of the Chambersburg-Hanover section. Base line along the southern boundary of the quadrangles. *Bottom:* projected profiles of the Hanover-Harrisburg section. Base line along the eastern boundary of the quadrangle.

CHAMBERSBURG-HANOVER SECTION

The Weverton (=Schooley) surface discussed above is present on this profile (Fig. 2, *center*) in the extreme eastern portion of the Chambersburg quadrangle and across most of the Fairfield quadrangle. Surrounding this isolated area assigned to the Weverton there is a lower, undulating surface which was correlated originally by Campbell with his Harrisburg erosion surface.

In 1933 M. R. Campbell abandoned the name Harrisburg and proposed the name Chambersburg in its place. Campbell states:

> The change of name from Harrisburg to Chambersburg for the most obvious geomorphic feature east of the Allegheny Front is desirable at this time, because areal work of a detailed character is now being carried on by the writer in the Piedmont Plateau, which has already resulted in the recognition of two other partial peneplains or berms of later date than the Chambersburg.[22]

Campbell at the present time considers that the type area of the Harrisburg at Harrisburg, Pennsylvania, represents a portion of the Bryn Mawr berm. The writer is not able to agree with this change in nomenclature. Field studies and projected profiles indicate that the original correlation was the correct one. The surface near Chambersburg may be traced to Harrisburg and so far as can be observed is the same surface. Therefore, the name Harrisburg must be retained, and the newer name Chambersburg must be discarded.

[20] *Ibid.*, p. 755.

[21] "Correlation of Appalachian Peneplanes," *op. cit.*, p. 204.

[22] "Chambersburg (Harrisburg) Peneplain in the Piedmont of Maryland and Pennsylvania," *Bull. Geol. Soc. Amer.*, Vol. XLIV (1933), pp. 556–57.

HANOVER-HARRISBURG SECTION

The lower surface, which has been discussed in connection with the Chambersburg-Hanover section, is observed on this profile (Fig. 2, *bottom*). Only one other surface is shown. The tops of the high ridges may be considered to mark the trace of a surface which has been nearly destroyed by the extension of the lower surface.

Fridley[23] presents an interpretation of the Harrisburg quadrangle in which he recognizes five surfaces, some of which were projected onto the Harrisburg quadrangle from quadrangles to the north. The projected profile drawn by Fridley has the eastern edge of the Harrisburg quadrangle for a base line, as does the profile accompanying this article. The difference in appearance is due to a slight modification in projecting the summits beyond the base line.

The surfaces which Fridley assigns to the Harrisburg area are as follows: (1) Kittatinny (about 1,650′); (2) Schooley (about 1,300′); (3) Mine Ridge (about 1,100′); (4) Honeybrook (about 900′); (5) Harrisburg (560′–600′). Ver Steeg,[24] however, identifies only two surfaces on this quadrangle. These are: (1) Schooley (Kittatinny), from 900′ to 1,680′, of which the higher elevations represent monadnocks of the Schooley (Kittatinny) surface; (2) Harrisburg, from 500′ to 700′, average 500′ to 540′.

The interpretation of the writer is in agreement with that presented by Ver Steeg, but Ver Steeg undoubtedly allows too much relief for the Schooley surface. The lower summits (900+ feet) should be considered monadnock areas rising above the Harrisburg surface but reduced so much that they cannot be considered portions of the Schooley surface or the trace thereof.

SUNBURY-MAHANOY SECTION

HAZLETON–DELAWARE WATERGAP SECTION

These two sections are treated as a unit, inasmuch as the Sunbury-Mahanoy section (Fig. 3, *top*) is the westward continuation of the Hazleton–Delaware Watergap section (Fig. 3, *upper center*). Three additional profiles are presented of the Shamokin, Hazleton,

[23] *Op. cit.*, p. 124, Fig. 5.

[24] "Some Features of Appalachian Peneplanes," *Pan.-Amer. Geol.*, Vol. LIV (1930), pp. 20–22.

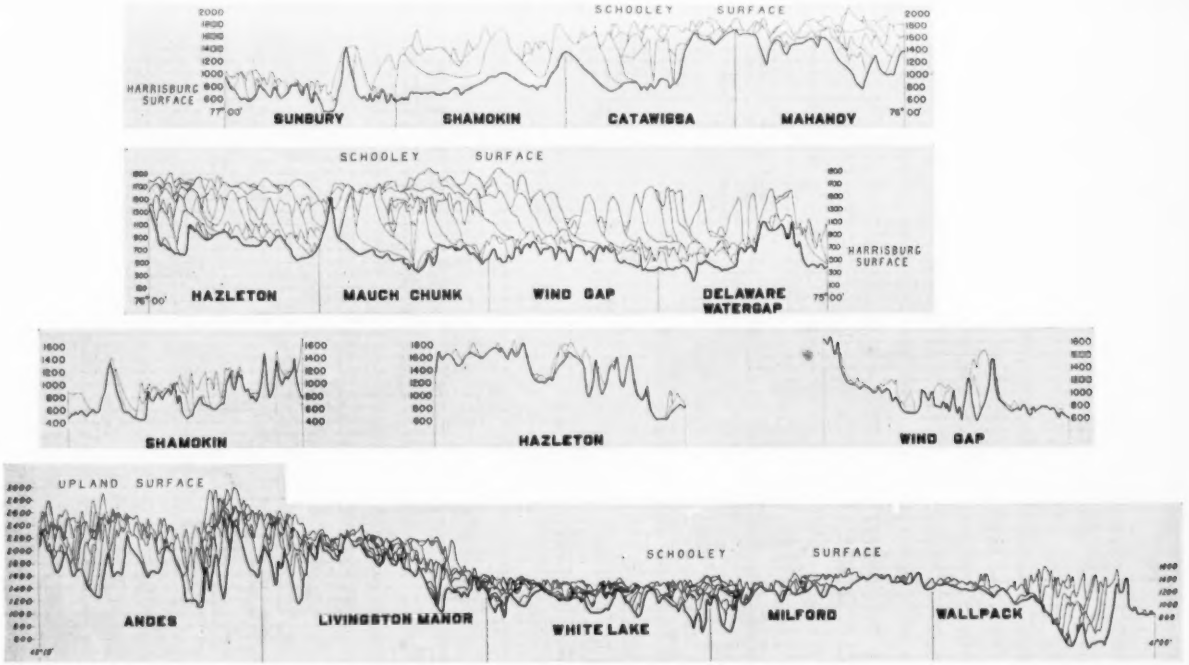

FIG. 3.—*Top:* projected profiles of the Sunbury-Mahanoy section. Base line along the southern boundary of the quadrangles. *Upper center:* projected profiles of the Hazleton-Watergap section. Base line along the southern boundary of the quadrangles. *Lower center:* projected profiles of the Shamokin, Hazleton, and Wind Gap quadrangles. Base line extends northwest-southeast across the quadrangles transverse to the strike of the ridges. *Bottom:* projected profiles of the Wallpack-Andes section. Base line along the western boundary of the quadrangles.

and Wind Gap quadrangles (Fig. 3, *lower center*). These profiles were constructed with the base line drawn normal to the strike of the dominant ridges.

Projected profiles of the Sunbury quadrangle have been published by Fridley[25] and by Ver Steeg.[26] The profiles of this quadrangle by these authors were constructed on a north-south base line, while the present profile was constructed on an east-west base line. Fridley and Ver Steeg have published profiles of the quadrangles north and south of the Sunbury quadrangle. Fridley identifies six erosion surfaces in the area adjacent to the Sunbury quadrangle, but Ver Steeg recognizes only two in this same area. The present profiles show only two surfaces on the Sunbury quadrangle.

Eastward from the Sunbury quadrangle two interpretations may be given to the profiles: (1) There are two surfaces. (2) There are three surfaces.

If two surfaces are recognized, all the crests above 1,400+ feet must be assigned to the upper surface, while the lower is maintained by hilltops between 700 and 1,000 feet. If three surfaces are recognized, the upper must truncate the crests between 1,900 and 2,000+ feet. The intermediate surface is maintained between 1,400+ and 1,700+ feet, while the lower surface is preserved by hilltops between 700 and 1,000 feet.

The writer believes that the interpretation of only two surfaces in this area is the correct one. This is predicated on the idea that the peneplanation of an area is completed first at the coast and gradually proceeds inland. If an area is uplifted, the new erosion surface may be completed in its turn at the coast, although areas of the initial erosion surface survive at the headwaters of the streams and in the interstreamal divides.

In a former article the Upland surface was recognized on the Penfield to Lock Haven quadrangles[27] at elevations of 2,200–2,400

[25] "Identification of Erosion Surfaces in South-central New York," *Jour. Geol.*, Vol. XXXVII (1929), p. 124, Fig. 5.

[26] "Some Features of Appalachian Peneplanes," *op. cit.*, Pl. II.

[27] "Development and Structural Control of Erosion Surfaces," *op. cit.*, pp. 147, 150, Fig. 3.

feet. This surface, if extended eastward, would pass over the tops of the highest ridges of the quadrangles under discussion.

In refuting this, some might regard the lower elevations as the result of the slope of the initial peneplain. If this were true there should be a progressive decline in elevation of the upper surface from west to east. Instead, there is a culminating area on the Mahanoy quadrangle with a slightly descending slope east and west. It is significant that these slopes are toward the major streams, the Delaware River on the east and the Susquehanna on the west.

ANDES-WALLPACK SECTION

Two surfaces are ideally represented on this section (Fig. 3, *bottom*). The lower one, extending from the Wallpack quadrangle to the northern edge of the White Lake quadrangle, represents the Schooley; the upper surface, illustrated by the projected profile of the Livingston Manor and the Andes quadrangles, is the Upland surface.

The lower surface is the one which S. C. Happ[28] has named the Monticello erosion level. Although Happ discusses the possibility that the Monticello surface might be a summit peneplain in this area, he favors a subsummit position. Moreover, he suggests a correlation of the Monticello surface with the Schooley. Below the Monticello surface Happ recognizes the Harrisburg and Somerville surfaces. The interpretation advanced in this article is in general accord with the correlations suggested by Happ.

The Schooley (Monticello) surface rises northward and merges with the so-called 2,000-foot level of the Catskills.[29] Above this is the Upland surface. This upper surface may be traced across the summits of the Catskills. As shown on the Livingston Manor and Andes quadrangles, the Upland surface is extremely fragmentary because of dissection in Schooley time. This is to be expected, as it represents a much greater time during which erosion has been active. This same condition prevails in the other areas of the Upland surface, which have been studied in detail.

[28] "Geomorphic History of the Minisink Valley Region," *Jour. Geomorph.*, Vol. I (1938), p. 202.

[29] G. H. Chadwick, "Discussion of 'Studies in Appalachian Mountain Sculpture,'" *Bull. Geol. Soc. Amer.*, Vol. XLVI (suppl., 1936), p. 2056.

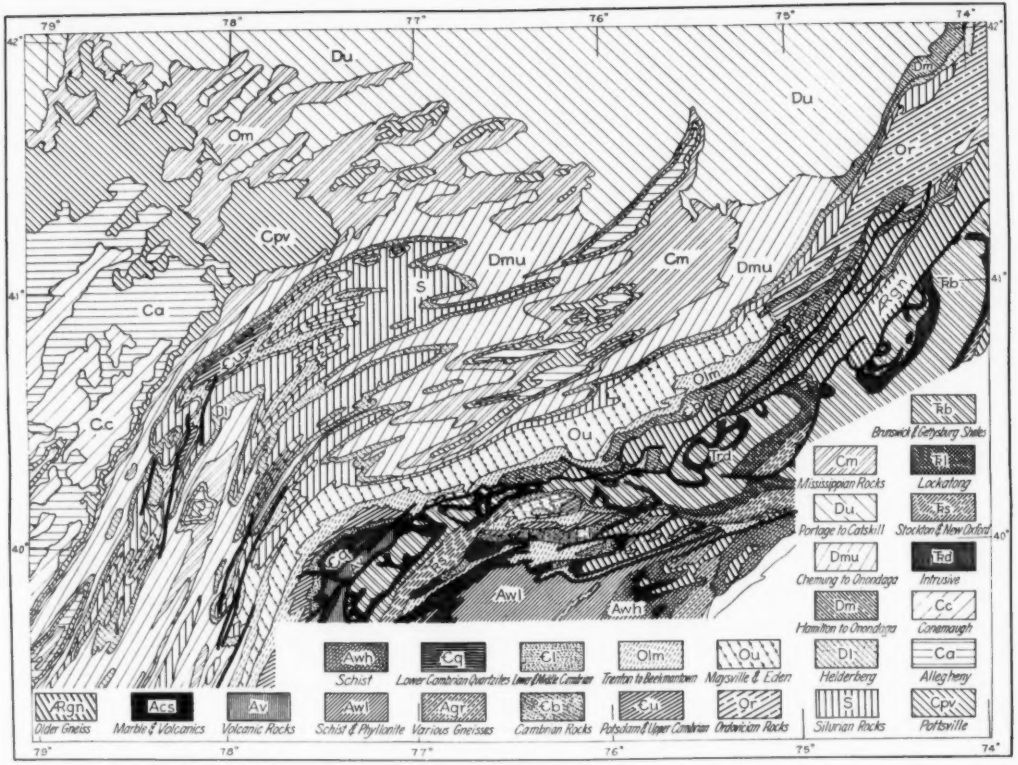

FIG. 4.—Areal geologic map

FIG. 4.—Areal geologic map

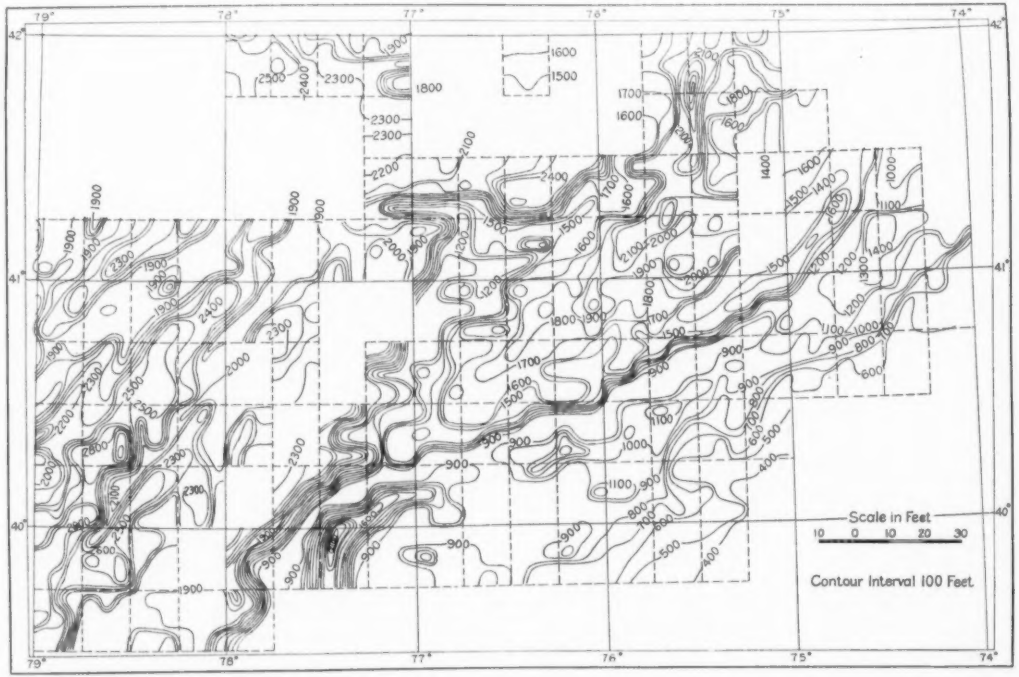

FIG. 5.—Contour map, drawn from the maximum elevations, to show the major features and areal expression of the erosion surfaces.

COMPARISON OF THE CONTOUR AND AREAL GEOLOGIC MAPS

The most striking fact which a comparison of these maps (Figs. 4 and 5) indicates is the parallelism between the trend of the contours and the geologic boundaries. It may be noted also that the greater areas of higher elevations are developed in the areas of slightly deformed rocks. The role of structure in the preservation and configuration of erosion surfaces is thus emphasized. But the western portion of the contour map shows that the Upland surface has been dissected by straths of younger surfaces which have extended into it. These straths occur only along major drainage lines.

AGE OF THE EROSION SURFACES

In the analysis of the erosion surfaces of Ohio, the writer concluded that little could be stated concerning the age of the surfaces in this locality except that the Parker strath was developed preglacially, inasmuch as its development was checked by the advance of the Pleistocene ice sheet.[30] But, it was suggested that the Upland surface might be the erosional equivalent of the Fall Zone peneplain.[31] This view, particularly with regard to the age of the oldest surface in the northern Appalachian Highland region, is in marked contrast to the opinions expressed by Shaw, Johnson, and Ashley, who consider the surfaces of this area to have been developed during much later geologic time.

Recently G. W. Stose[32] has argued that the major development of the Schooley surface occurred during Jurassic time. However, Stose does not recognize the existence of any older surface than the Schooley in the northern Appalachian region. The profiles accompanying this article, as well as those previously published by the writer, are believed to demonstrate the existence of an older surface (Upland) with which the Schooley surface interfingers on the east and the Allegheny on the west.

If the Schooley is assigned to Jurassic time, the question may be raised regarding the age of the Upland surface. H. A. Meyerhoff

[30] "Development and Structural Control of Erosion Surfaces," *op. cit.*, p. 157.

[31] "Identification of Erosion Surfaces in Eastern and Southern Ohio," *ibid.*, Vol. XLII (1934), p. 288.

[32] "Age of the Schooley Peneplain," *Amer. Jour. Sci.*, Vol. CCXXXVIII (1940), pp. 461–76.

and E. W. Olmsted[33] have suggested that the main streams of the northern Appalachian region had their initiation in Permo-Triassic time. It may be that the Upland surface reached its maximum development at that time. The Upland surface is fragmentary and preserved only upon the areas of most resistant rocks. Moreover, it is found mainly in headwater regions of the stream systems. These structural and topographic conditions favor the preservation of an erosion surface during long geologic time.

In opposition to the view that the erosion surfaces of the Appalachians are old geologically, G. H. Ashley has stated that "the Schooley peneplane may be of late Pliocene age, and possibly only one or two million years old. . . . ."[34] More recently he has assigned an age in years of 6,400,000 since the beginning of uplift of the Schooley surface. This figure[35] was based on the assumption that divides are reduced about one foot in 4,000 years.

Chadwick, however, has advanced another opinion, as may be seen from the following quotation:

> Meantime, the Catskills throw another ray of light on the lowering of divides, for glacial striae of early Wisconsin time are perfectly preserved on the extreme tip of their highest peak, as verified by Leverett and Antevs, thus showing no lowering at this point in perhaps half a million years.[36]

As has been previously noted, the Parker strath was developed just prior to the advance of the Pleistocene ice. In fact the development of this erosional stage was halted by that advance. A similar history is shown by the Somerville strath at its type locality at Somerville, New Jersey, as this strath is in part overlain by deposits of supposed Jerseyan drift.[37] The age of the Parker strath and Somerville strath is definitely late Pliocene.

Stose presents reasonable evidence that the development of the Schooley surface occurred during Jurassic time, although the maximum dissection of this surface may not have occurred until mid-

[33] "The Origins of Appalachian Drainage," *Amer. Jour. Sci.*, Vol. XXXII (1936), pp. 21–42.

[34] "Studies in Appalachian Mountain Sculpture," *op. cit.*, p. 1436.

[35] From typewritten abstract and an address presented at Harrisburg, Pa., September 1, 1939.

[36] *Op. cit.*, pp. 2056–57.

[37] Raritan Folio 191, *U.S. Geol. Surv.* (1914).

Tertiary. Thus there are rather satisfactory determinations of the age of two of the erosion surfaces of the Appalachians.

With regard to the Upland surface, the only statement which may be made at the present time is that it is pre-Schooley in age. The Harrisburg surface is post-Schooley and pre-Somerville in age.

As more detailed and accurate results of seismic refraction measurements become available, it may be possible to trace all the erosion surfaces beneath the sediments of the coastal plain. W. T. Thom, Jr.,[38] has already constructed a very suggestive map showing by contours the configuration of the basement, the base of the Eocene, and the base of the Miocene.

SUMMARY

Within the Appalachian Highland area of Pennsylvania, eastern Ohio, eastern Kentucky, southern and central New York, there have been developed erosion surfaces and straths which may be correlated. The Upland surface, the only true peneplain, is common to both the eastern and the western areas. The Schooley erosion surface of the eastern portion is the erosional equivalent of the Allegheny surface of the western area. The Harrisburg surface of eastern Pennsylvania has its contemporary in the Lexington surface of Ohio and Kentucky. The strath stage, or youngest surface, of marked regional development is known as the Somerville strath in New Jersey and adjacent areas of Pennsylvania. It is correlated with the Parker strath of western Pennsylvania, eastern Ohio, and Kentucky.

The correlations have been substantiated by means of field studies in conjunction with projected profiles. Although structure plays an important role in the configuration of the erosion surfaces, it may be evaluated particularly in the plateau area. Once the erosional history is deciphered in the areas of comparatively simple structure, detailed analysis may be made in more complex areas. The conclusions drawn in former articles by the writer seem to be valid.

ACKNOWLEDGMENTS.—The writer gratefully acknowledges his indebtedness to the Graduate School of the Ohio State University for financial assistance in the preparation of certain illustrations used in this paper.

[38] "Position, Extent and Structural Makeup of Appalachia," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), Fig. 1, opposite p. 316.

THE FAMILY TREMATOPSIDAE

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ABSTRACT

The family Trematopsidae is expanded to include the genus *Acheloma* as well as *Trematops*. The former occurs in the Wichita and Putnam formations of Texas, while the latter is found in the Clear Fork formation. The revised and amended descriptions point out the many similarities between the two genera. Two new species of *Acheloma* are erected on the basis of new material. There is a rather wide variation of many characters within the species of these two genera, but certain constant features of the skull and postcranial skeleton separate them clearly. The family is more closely related to the family Dissorophidae than to any other known from the Texas red beds. The members of the genus *Trematops* were very active, terrestrial carnivores, while those of the genus *Acheloma*, also carnivores, seem to have spent much of their life in and close to water.

INTRODUCTION

The family Trematopsidae was proposed by S. W. Williston[1] to include *Trematops*. *Acheloma* was tentatively referred to the family, but this assignment has never been very generally accepted. D. M. S. Watson[2] proposed the family Achelomidae, but it is now clear that *Acheloma* and *Trematops* are very closely related and should be placed in the family proposed to include the latter by Williston. Until recently it has been thought that specimens of these genera were rare, but since about 1934 many have been added to the collections of Walker Museum and the Museum of Comparative Zoölogy of Harvard University, so that about thirty specimens are now available for study.

SYSTEMATIC REVISION

Class Amphibia

ORDER LABYRINTHODONTIA

SUBORDER RHACHITOMI

FAMILY TREMATOPSIDAE

Williston's original description of the family is as follows:

A median foramen back of premaxillae; large antorbital vacuities. Otic notch wholly enclosed by bone, the opening small and extending far forward.

[1] "*Cacops, Desmospondylus*, New Genera of Permian Vertebrates," *Bull. Geol. Soc. Amer.*, Vol. XXI (1910), pp. 249–84.

[2] "The Structure, Evolution, and Origin of the Amphibia: The 'Orders' Rhachitomi and Stereospondyli," *Phil. Trans. Roy. Soc. London*, B, Vol. CCIX (1919), pp. 1–72.

Palate with two pairs of large teeth back of the nares and a single one on each vomer. No parasphenoid. Ribs short, the anterior ones expanded distally. Twenty-two or twenty-three presacral vertebrae; a single sacral; tail short. No dermal armour or carapace. Cleithrum unknown. Clavicles and interclavicle small, without dermal pittings. Humerus with entepicondylar process.

It is now necessary to revise this description and to amend it to include the genus *Acheloma*. E. C. Case[3] revised Williston's original

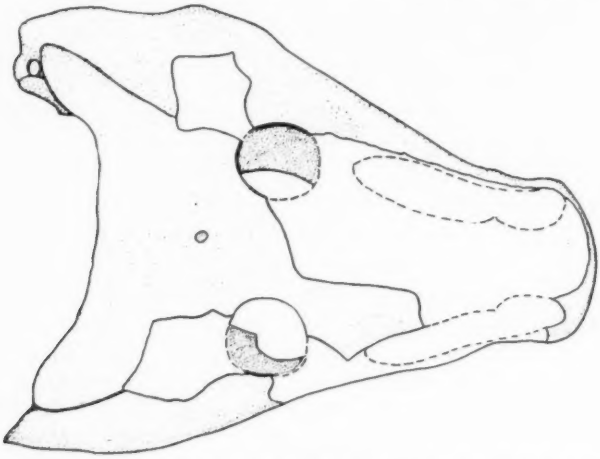

FIG. 1.—*Acheloma cumminsi* Cope. Skull of holotype, A.M. 4205. Dorsal aspect. ×½

definition, but considerable information has come to light since his work was published. The revised and amended diagnosis is as follows:

Skull roughly triangular; nares joined posteriorly to antorbital fossa; a median narial opening lying between premaxillaries and nasals; otic notch deep, often closed posteriorly by the junction of the long, hornlike projection of the tabular and a short process of the quadrate. Pineal opening present; occipital condyle parial; parasphenoid present, extended anteriorly in large, heart-shaped vacuity as slender rostrum of unknown anterior termination. Marginal teeth labyrinthine, long and tapering, with greatest elongation under orbital and narial regions; one set of prevomerine and two of palatine

[3] "Revision of the Amphibia and Pisces of the Permian of North America," *Carnegie Inst. Wash. Pub. 146* (1911).

teeth. Twenty-two to twenty-four presacral, one sacral, and an indeterminate number of caudal vertebrae. Coracoids often unossified; cleithrum present; blade of scapula sometimes inflected posteriorly and sometimes upright and expanded dorsally. Humerus with no entepicondylar foramen. Carpals and tarsals often well ossified. Femur long with strong adductor ridge. Humerus, femur, pectoral and pelvic girdles often poorly ossified. Ribs expanded in pectoral region. No dermal armor.

GENUS *Acheloma* COPE

Genotype.—*Acheloma cumminsi* Cope, A. M. 4205.

Horizon and locality.—The specimen is listed only as from the Permian of Texas. The nature of the preservation, the type of matrix, and the similarity to referred specimens from the Wichita formation suggest that the genotype comes from the Wichita. All other specimens which can be placed in this genus occur in the Wichita or Putnam formations.

Original description.—E. D. Cope's[4] original description of the genus has been repeated by Case.[5] It is rather long and contains some statements not needed in a pure description. It is repeated here in synoptic form only:

> Differing from *Eryops* in the absence of notch of the posterior border of the skull between the epiotic and the quadrate or squamosal bones, and in complete absence of condyles of the humerus.
>
> Mandible without angular process. Teeth of jaws subequal, rather larger anteriorly; some large ones on the *os palatinum* at different points along the internal margin. Pterygoid bone ending in a free, decurved edge anterior to the quadrate bone. Palatines and pterygoids narrow, leaving a wide palatal foramen. Vertebrae in their principal features as in *Eryops*. The humerus . . . . resembles one figured by Gaudry as belonging to *Actinodon*, except that in *Acheloma* there are no condyles and there is an epicondylar foramen. . . . .

On the basis of a restudy of the genotype and of new material this description may be revised and amended as follows: Nares far forward; internarial opening varying from large to very small. Pineal opening large to small, lying just back of level of posterior margins

[4] "Third Contribution to the History of the Vertebrata of the Permian Formation of Texas," *Proc. Amer. Phil. Soc.*, Vol. XX (1882), p. 455.

[5] *Op. cit.*, p. 38.

of orbits. Tabulars small; premaxillaries short; posterior extension of maxillaries not reaching level of otic notch; squamosals large. Scapular blade inflected posteriorly and little expanded; coracoids little ossified except in very large specimens; postcoracoid region

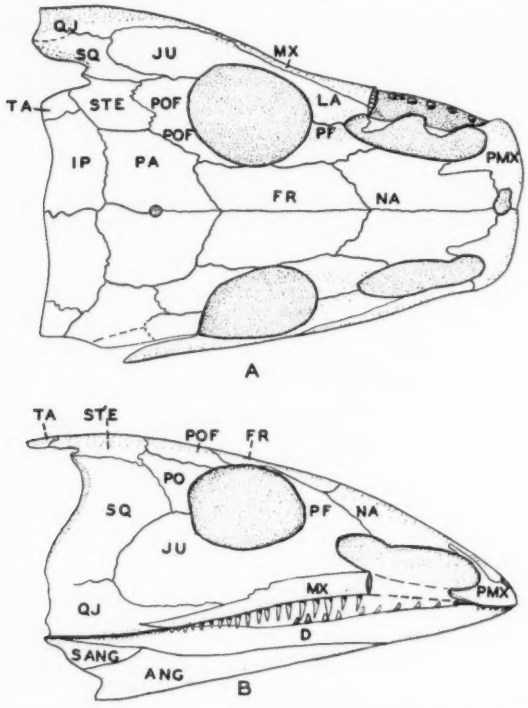

FIG. 2.—*Acheloma cumminsi* Cope. Skull of referred specimen, M.C.Z. 1414. *A*, dorsal aspect; *B*, lateral aspect (this figure represents the left side of the specimen, which is more nearly complete and which has been reversed so that the positions of the elements correspond to those of the dorsal aspect). ×1.

short. Femur, humerus, and pelvic girdle poorly ossified except in very large specimens. Condyles present on humerus when ossification is complete. Femur and humerus massive when fully ossified. Hypocentra crescentic with no ossification dorsal to notochordal notch.

Acheloma cumminsi COPE

Holotype.—Same as genotype.

Original description.—The original description of the species is long. The important points are summarized in the following passage:

Skull triangular; posterior table flat with decurved lateral edges resting on squamosal or quadratojugal and quadrate bones. Quadrate sloping posteriorly and downwards. Mandibular ramus strongly incurved posteriorly; mandibular symphysis short. Teeth slightly longer on premaxillary than maxillary; palatine teeth large. Intercentra of vertebrae ossified to nearly cut off chorda dorsalis. Scapula robust, flat, with posterior-external border longest. Coracoid appearing to be coossified with scapula, directed downwards and backwards; epicoracoid, if it existed, lost. Plate of scapula horizontal transversely, inclined upwards and posteriorly at 30°. Coracoid vertical. Epitrochlear foramen present, protected by strong ridge.

Revised and amended description.—Scapular blade strongly inflected posteriorly. Confluent opening of narial and antorbital fossae long; dermal surface of skull deeply pitted; preorbital region of skull long; pineal opening proportionately large; interparietal and tabular forming but small part of occipital slope. Internarial opening large.

TABLE 1

REFERRED SPECIMENS

M.C.Z. 1766	Large skull
M.C.Z. 1414	Small skull, Putnam formation, 1 mile south of Archer City, Archer County, Texas
M.C.Z. 1413	Postcranial fragments, same horizon and locality as 1414
M.C.Z. 1490	Parts of skull and postcranium of several large individuals. Same locality as 1414

SKULL MEASUREMENTS

Specimen	Length from Dorsal Margin of Occiput to Snout
A.M. 4205	155 mm.
M.C.Z. 1414	74
M.C.Z. 1766	148

Acheloma pricei N. SP.

Holotype.—*Acheloma pricei*, M.C.Z. 1419. Skull.

Horizon and locality.—Putnam formation, 1 mile south of Archer City, Archer County, Texas.

TABLE 2

PARATYPES

M.C.Z. 1420	Skull. Horizon and locality same as holotype
M.C.Z. 1421	Skull. Horizon and locality same as holotype
M.C.Z. 1772	Occiput of skull. Horizon and locality same as holotype

Diagnosis.—Surface pitting of dermal surface of skull very fine, pits circular. Confluent opening of narial and antorbital fossae short. Preorbital region of skull short; internarial opening very small; pineal

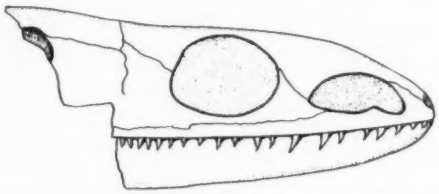

FIG. 3.—*Acheloma pricei* n. sp. Holotype, M.C.Z. 1419. Lateral aspect. ×1

opening proportionately large, near level of posterior margins of orbits. Interparietal and tabular extended well down onto occipital plate. Occiptal and temporal regions low.

TABLE 3

SKULL MEASUREMENTS

Specimen	Length from Dorsal Margin of Occiput to Snout
M.C.Z. 1419	63 mm.
M.C.Z. 1420	56
M.C.Z. 1421	62

This new species is named in honor of Mr. L. I. Price, who has been instrumental in collecting and studying much new material from the red beds of Texas and Oklahoma.

Acheloma whitei N. SP.

Holotype.—*Acheloma whitei*, M.C.Z. 1767. Skull.

Horizon and locality.—Witchita formation. One and one-half miles west of Williams Ranch, Baylor County, Texas.

TABLE 4

PARATYPES

M.C.Z. 1771.....Parts of several skulls and much associated postcranial material. Horizon and locality same as holotype

Diagnosis.—Pineal opening very small lying at level of posterior margins of orbits. Confluent opening of narial and antorbital fossae very short. Skull pitting fairly deep and coarse, pits irregular in shape. Internarial opening large. Interorbital width great, maxillary relatively short. Skull length about 60 mm.

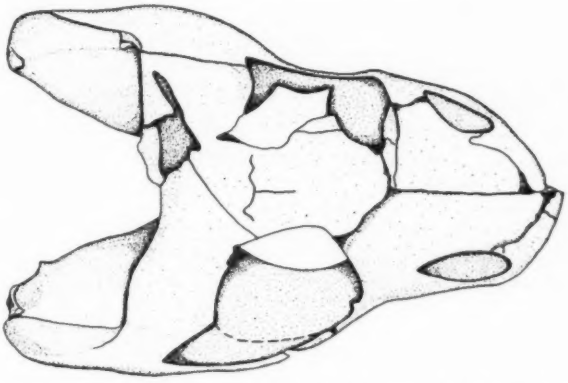

FIG. 4.—*Acheloma whitei* n. sp. Holotype, M.C.Z. 1766. Dorsal aspect. ×1

From the postcranial material associated with the holotype and paratypes, it is apparent that all the elements are small in proportion to the size of the skull and that ossification is relatively incomplete. The hypocentral elements are crescentic and similar in appearance to those of *Trimerorhachis*. The femur is much smaller than that in a specimen of *Trematops* of comparable size and much less ossified. It may be that all the known specimens, coming as they do from a single pocket, are immature, but even if this is the case, the skull characters are such that there is little chance of the specimens representing the young stage of any of the large specimens of other species.

GENUS *Trematops* WILLISTON

The original description of the genus and species was given by Williston,[6] but no separate generic diagnosis was given. Case[7] abstracted Williston's description and revised it. The original description is too long to permit repetition here, comprising as it does almost a complete paper, but in the following passage certain parts which apply to the genus are repeated:

> A median, unpaired opening on the anterior portion of the snout opening into a palatine vacuity. Two large antorbital openings perhaps the nares, with septomaxillary bones. Temporal fenestrae present. Parasphenoid absent (?). Two sacral vertebrae. Vertebrae rhachitomus.

Revised and amended description.—Dermal pitting of skull deep and coarse. Nares relatively far back from tip of snout; confluent opening of nares and antorbital fenestra long. Otic notch open posteriorly, shelf on ventral margin of otic notch well defined and broad. Maxillary projecting back of level of anterior margin of otic notch. Tabular broad, frontals short, nasals long, premaxillaries short, squamosals small. Pineal opening large, somewhat posterior to margins of orbits. Internarial opening usually large, possibly absent in one form. Scapular blade uninflected, expanded dorsally. Coracoids well ossified even in young individuals; postcoracoid region long. Hypocentral elements of presacral vertebrae ossified to form a complete ring of bone around notochordal canal. Ossification of skeleton occurring in much younger stage than in *Acheloma*.

Trematops milleri WILLISTON

Holotype.—W.M. 640. Skull and partial skeleton.

Horizon and locality.—Clear Fork formation, Brushy Creek, Baylor County, Texas.

Original description.—Neither Williston's paper nor Case's revision gives a description of the species separate from that of the genus.

Revised and amended description.—Internarial opening always large. Eighteen to 25 maxillary and premaxillary teeth. Length of fossa of antorbital fossa and narial opening variable in length. Otic

[6] "New or Little Known Permian Vertebrates: *Trematops*, New Genus," *Jour. Geol.*, Vol. XVII (1909), pp. 636–58.

[7] *Op. cit.*, p. 67.

notch deep, restricted medially, closed posteriorly. Vertical extent of ramus of lower jaw restricted posteriorly. Mature skulls over 150 mm. in length.

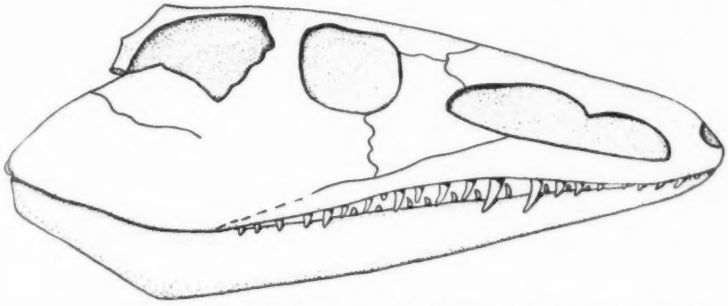

FIG. 5.—*Trematops milleri* Williston. Skull of holotype. W.M. 640. Lateral aspect. ×3/10.

TABLE 5

SKULL MEASUREMENTS

Specimen	Length from Top of Occiput to End of Snout
W.M. 640	178 mm.
W.M. 1759	155
W.M. 1760	162

REFERRED SPECIMENS

W.M. 1756.....Partial skull and postcranial skeleton lacking caudal vertebrae, most of phalanges, and some ribs. Mounted in Walker Museum. Clear Fork formation, East Coffee Creek, Baylor County, Texas

W.M. 1759.....Skull and lower jaws. Clear Fork formation, East Coffee Creek, "Broiliellus Bone Bed," Baylor County, Texas

W.M. 1760.....Skull and lower jaws. Same locality as 1759

Trematops willistoni N. SP.

Holotype.—Skull and lower jaws with associated postcranial material. W. M. 1584.

Horizon and locality.—Clear Fork formation, West Coffee Creek, Baylor County, Texas.

Diagnosis.—Mature skulls about 70 mm. in length. Otic notch open posteriorly, no medial restriction. Narial openings proportionately shorter than in *T. milleri*. Ramus of lower jaw deep posteriorly.

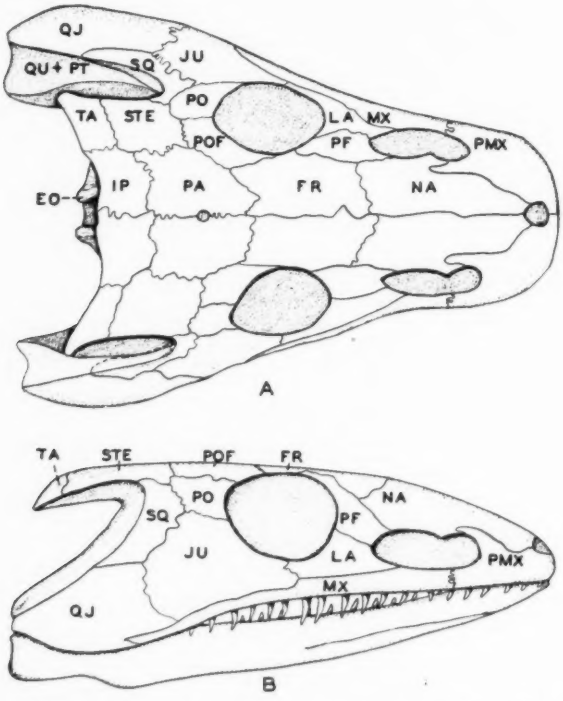

FIG. 6.—*Trematops willistoni* n. sp. Skull of holotype. W.M. 1584. *A*, dorsal aspect; *B*, lateral aspect. ×1.

Trematops thomasi MEHL[8]

Holotype.—Anterior part of skull in collections of the University of Missouri.

Horizon and locality.—Clear Fork formation, 10 miles south and somewhat east of Snyder, Oklahoma.

[8] M. G. Mehl, "*Trematops thomasi*, a New Permian Amphibian Species from the Permian of Oklahoma," *Jour. Geol.*, Vol. XXXIV (1926), pp. 466–74.

TABLE 6

SKULL MEASUREMENTS

Specimen	Length from Top of Occiput to End of Snout
W.M. 1584	70 mm.
W.M. 1585	72

REFERRED SPECIMEN

W.M. 1585.....Half skull. Clear Fork formation, West Coffee Creek, Baylor County, Texas

Discussion.—The original description of this form comprises the complete paper by Mehl. The main bases for the establishment of a new species are the lack of an internarial fossa and the small size of the specimen. The other characters fall within the range of variation of *T. milleri*. The size is not sufficiently different to be an accurate basis for specific separation. Mehl states that there is a separation of the premaxillaries in the area in which the internarial fossa might be expected. This same condition occurs in certain specimens of *Acheloma* and tends to obscure the fossa. This may have been the case in the holotype of *T. thomasi*. If the fossa is actually absent, it would appear to indicate that the specimen is correctly referred to a different species, but, if it is present even as a small structure, there is no particular reason for separating this specimen from *T. milleri*.

MORPHOLOGY

The following discussion of the morphology of the skull and postcranial skeleton applies to the family Trematopsidae as a whole, with special reference to distinctions of genera and species where these are of importance. With the exception of a few major characters, members of the two genera show a marked similarity. The most important differences are characters influenced by the retarded ossification in *Acheloma*, the structure of the pectoral girdle, and the positions of the fossae of the skull.

THE SKULL

The most accurate and complete description of the skull of any member of the family has been given by Williston[9] discussing *T. mil-*

[9] *Op. cit.*

leri. Most of his statements have been confirmed by the present work, and many of them apply to the family as a whole, but certain corrections and additions may be made.

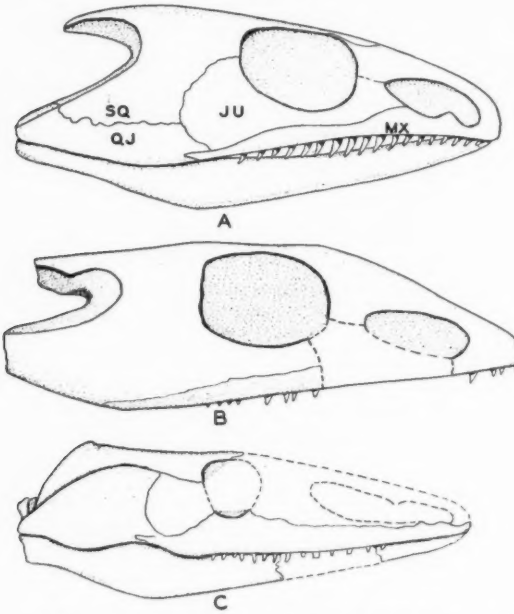

FIG. 7.—*A*, *Acheloma pricei* n. sp. Referred specimen, M.C.Z. 1421. Lateral aspect. ×1. *B*, *Trematops willistoni* n. sp. Referred specimen, W.M. 1585. Lateral aspect. ×1. *C*, *A. cumminsi* Cope. Skull of holotype, A.M. 4205. Lateral aspect. ×3/8.

Dorsal and lateral dermal surfaces.—The sutures between the component elements of the skull surface have been poorly preserved in all specimens described to the present time, except for *T. thomasi*. This specimen possesses only the snout and gives no indication of the conditions in the orbital, temporal, parietal, and occipital regions. The sutures of *T. milleri* as illustrated by Williston are correct except for the one between the nasal and the premaxillary, this being placed so that the premaxillary is much larger than previously supposed. The positions and proportions of the other elements of the skulls in this family are shown in Figures 2 and 6 and need little more discussion.

The squamosal is quite small, smaller in *Trematops* than in *Acheloma*, and the quadratojugal is very large. No suture appears in any specimen between the quadrate and the quadrate ramus of the pterygoid. The tabulars are relatively large in both genera but are larger in *Trematops* than in *Acheloma*. In both they extend laterally in a thin, curving, hornlike process above the otic notch. In some species they make contact with the dorsal process of the quadrate to close the notch posteriorly. In *T. willistoni* and apparently in the smaller species of *Acheloma* the contact is not attained.

The narial region of the Trematopsidae is peculiar and of considerable interest. This area is very well shown in *T. milleri*, W.M. 1759, and the following description is based on this specimen. Each long, lateral, narial opening is partially divided into an anterior and a posterior part by a constriction. The anterior portion is less extensive than the posterior. The internal naris lies under the posterior part only. Along the median wall of the internal naris the prevomer curves upward in a flange separating the naris from the medial portion of the skull. Just medial to this flange there is a curved, descending septum of the nasal. The prevomerine internasal septum divides the snout into two lateral halves. The result of the arrangement of these septae is a chamber partially divided into two parts by the nasal septum. The chamber opens anteriorly into the forepart of the external narial vacuity. It does not come in contact with the median narial opening, the posterior portion of the paired narial openings, or with the internal naris. The precise meaning of this structure is not clear, but it is significant that the internal naris lies below only the posterior part of the external naris and that the chamber in the snout communicates only with the anterior part of the external naris. The chamber probably housed Jacobson's organ or a similar structure. The suggestion is that the anterior part of the external naris was concerned primarily with the sense of smell, while the more posterior part functioned principally as an air intake. It has been suggested previously that the posterior part housed a gland of some sort. While this is possible, the structure outlined above makes it seem rather improbable. Both Williston and Mehl have described a septomaxillary bone as being present. None can be iden-

tified in the specimens studied, and it is probable that they took either the nasal or the prevomerine septum to be this element.

The median narial opening opens directly into the oral cavity and does not pass through any bones of the palate. To all appearances it functioned as accessory breathing apparatus.

The pineal opening is always present, but it is very small in *A. whitei*. Its position varies in different genera and species.

Occipital and palatal regions.—The interparietal and tabular form the dorsal part of the occiput, and there is no external development of the supraoccipital. In most species the ventral extent of the tabulars and interparietals is slight, but in *A. pricei* both are extended well down over the paroccipital process near the junction of the two dermal elements. Within the brain case a well-ossified supraoccipital is present, underlying the interparietal and joining the otics laterally. Its anterior margin appears to have been cartilaginous.

The exoccipitals are very large and form the facets of the double condyle as well as the lateral margins of the foramen magnum. No openings through these bones have been found, and the hypoglossal foramina apparently were absent. A small jugular foramen passes between the exoccipital and the opisthotic on each side. The basioccipital presumably is represented by the basal element between the two exoccipitals, but there are no sutures to indicate its actual limits. It does not appear to have entered into the formation of the condyles.

The basisphenoid and parasphenoid are fused. Williston indicated tentatively that there was no parasphenoid in *Trematops*, but the bone actually is well developed. It is not clearly shown in the holotype of *T. milleri*, upon which Williston's account was based. The posterior extension of the parasphenoid lies beneath the basioccipital, forming a pair of tubera. Laterally the element forms the ventral margin of the fenestra ovalis, replacing the poorly ossified basioccipital functionally. A well-developed parasphenoid rostrum is present, but the character is more like that of a reptile than that of a normal rhachitomous amphibian. The rostrum passes forward as a slender process to articulate with the posterior end of the keel of the sphenethmoid. It passes forward under the sphenethmoid as a very thin splint. The exact level of anterior termination is not shown in

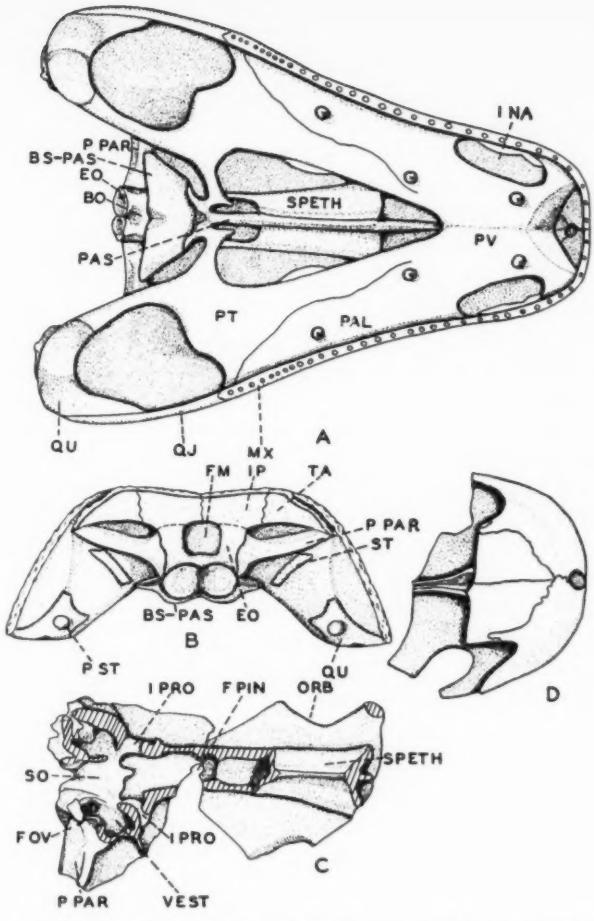

FIG. 8.—*A*, *Trematops*, composite palatal aspect. Based on W.M. 1584, 1585, 640, 1759, 1760, with certain details added from *Acheloma*, particularly M.C.Z. 1490. *B*, *Trematops*, composite drawing of occiput. Based largely on W.M. 1584. Extent of occiput based on condition in *Acheloma*, M.C.Z. 1490 and *Trematops*, W.M. 1760. *C*, Part of brain case of *A. cumminsi* Cope, based on M.C.Z. 1490. It is not certain that the anterior and posterior portions are parts of the same specimen, but the position of the pineal, partially preserved in both, permits the orientation for reconstruction. *D*, *Trematops* sp. indet. Snout in dorsal aspect to show the nature of the prevomerine internasal septum. The condition of the sutures is slightly different than that in any other known specimen.

any specimen, but it is certain that the rostrum did not pass forward of the anterior margin of the interpterygoidal vacuity. It did not make contact with the anterior margin of the vacuity but lay well above the level of the pterygoid and palatine.

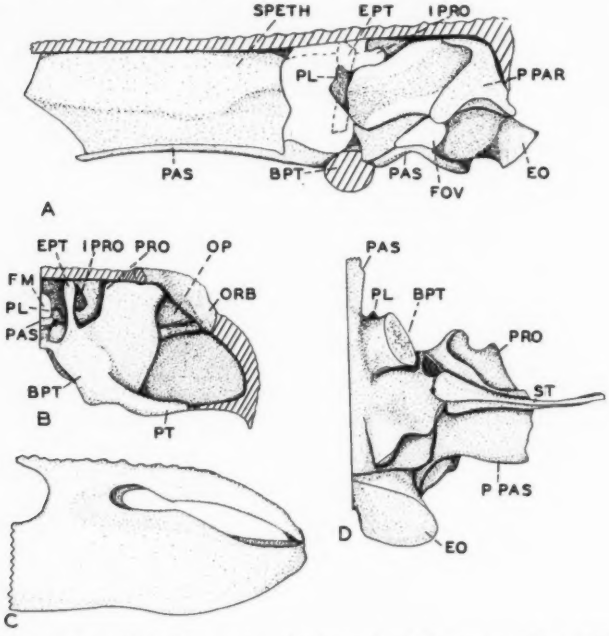

FIG. 9.—Details of the brain case and otic notch of *Trematops milleri* Williston, based on W.M. 1760. *A*, Lateral aspect of brain case with dermal and palatal surfaces of skull removed. ×1 *B*, Anterior aspect of pterygoid and epipterygoid showing relations to otic part of brain case. ×½. *C*, Lateral aspect of otic notch. ×½. *D*, Ventral aspect of posterior part of brain case. ×1.

The nature of the joint between the basicranium and the palate is shown in Figure 8, *A*. In *T. willistoni*, from which this drawing was prepared, the joint is weak, and no suture is present. In *T. milleri* the joint is somewhat heavier, and a closely knit suture is developed. The parasphenoid does not appear to have participated in the formation of the joint. There is no evidence of any foramina for the internal carotid arteries, and it seems probable that they entered the

cranial cavity through the notch between the pterygoid and the posterior termination of the rostrum of the parasphenoid.

Few of the palatal sutures are well developed in any specimen. The largest element is the pterygoid, which is composed of a very strong quadrate ramus, a poorly defined transverse process, and an anterior ramus which encloses much of the interpterygoidal vacuity. The anterior termination of the bone is not entirely certain, but in *T. thomasi* it does not reach the anterior margin of the interpterygoidal vacuity. Above the joint of the palate and brain case the pterygoid rises as a thin septum which is continuous with the dorsal part of the quadrate ramus. The medial margin of the septum is directly above the joint of the palate and brain case. Medial to it the slender, rodlike epipterygoid rises to the roof of the skull. The pterygoid and epipterygoid are fused together at the base of the latter.

The anterior part of the prevomers curves dorsally to form a cup-shaped depression just back of the inner opening of the median narial fossa. Dorsally along the midline the prevomers form an internasal septum which very nearly divided the chamber of the snout into two lateral parts. Posterior to this is a very thin sheet of bone which appears to represent part of the sphenethmoid complex.

Brain case.—The ventral aspects of the basisphenoid, basioccipital, and parasphenoid have been described. From the inside of the brain case it is apparent that neither the basisphenoid nor the basioccipital is well ossified. Little of the detail of the floor of the brain case is preserved. At the anterior end of the basisphenoid a pair of short, thick, pleurosphenoid elements are present. Much of the pila antotica appears to have been persistently cartilaginous.

On the anterior margin of the pro-otic there is a strongly developed pro-otic incisure partially enclosed ventrally by the pleurosphenoid. In one specimen of *Acheloma* the sphenethmoid passes back to the dorsal margin of the pro-otic partially enclosing the pro-otic incisure, but this condition does not appear to be characteristic of the family as a whole. No opening for the seventh cranial nerve has been found. The vestibule of the inner ear has an open connection with the cranial cavity, and no osseous record of a sinus utriculus or endolymphatic duct is present. Large ampuller recesses open directly into the

vestibule. There is little ossification in the region of the semicircular canals.

The sphenethmoid is a large, well-ossified element characteristically developed only anterior to the pineal foramen. The main body is Y-shaped, but anteriorly the lateral wings are separated by a median septum. In one specimen this septum appears to continue forward to the prevomerine internasal septum as a very thin vertical sheet of bone. There are no fenestra or foramina penetrating the lateral walls of the sphenethmoid.

Middle ear and quadrate bone.—The stapes is present in *T. milleri* (W.M. 1760) and in *T. willistoni* (W.M. 1584). In the former it is well ossified and passes from the large fenestra ovalis to the anterior

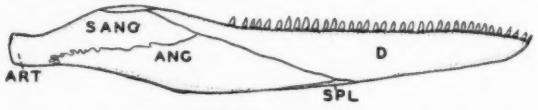

FIG. 10.—*Trematops*. Composite drawing of lower jaw. Based largely on W.M. 1584.

part of the otic notch. The foot is large, and the shaft is very slender. No processes occur on the shaft, and no stapedial foramen is developed. Ossification of the stapes in *T. willistoni* is incomplete. The stapes does not entirely fill the fenestra ovalis but leaves a small, triangular opening anteriorly. Whether this opening was functional or not has not been determined.

The quadrate is a relatively large element which forms the articular surface for the lower jaw. Rising above it is a process which in some species articulates with the tabular. At the base of this process a small rounded facet is developed. This is similar to the process in *Eogyrinus* described by D. M. S. Watson[10] and present in such forms as *Diadectes* and *Seymouria*. It is possible that it may represent a point at which a cartilaginous process of the stapes articulated with the quadrate.

Lower jaw.—Little description of the lower jaw is necessary, since much of what can be determined is shown in Figure 10. Details of

[10] "The Evolution and Origin of the Amphibia," *Phil. Trans. Roy. Soc. London*, B, Vol. CCXIV (1925), pp. 189–257.

the inner surface are apparent only near the back of the jaw. The articular and prearticular are separated by a suture, and a large foramen passes between them. The symphysis of the jaws is formed by the dentary and splenial.

Dentition.—The number of maxillary and premaxillary teeth varies considerably, ranging from about eighteen to forty. The teeth are closely spaced in the posterior part of the row but are rather far apart anteriorly. The longest teeth occur beneath the anterior part of the orbit and the posterior part of the narial fossa. The number of teeth and their size seem to be of no taxonomic significance. The usual positions of the palatine and prevomerine teeth are indicated in Figure 8, *A*. One or two teeth may be present in each locality. These teeth are larger than the marginal teeth and are more expanded basally. Like them, they are labyrinthine in character. The dentary teeth are similar to those on the maxillary and premaxillary and in the anterior part of the series alternate with the upper teeth in position.

In addition to the large palatal teeth there are very fine teeth developed on the transverse process of the pterygoid and on the palatine and prevomer. The latter are arranged in four rows, one passing back from each of the large prevomerine teeth and one along each side of the suture between the prevomers. These teeth are conical and do not show a labyrinthine character.

POSTCRANIAL SKELETON

Vertebral column.—For the most part the earlier descriptions of the column are correct, and only a few details can be added. No unquestionably complete vertebral column has yet been found, but in specimen 1756, *T. milleri*, mounted in Walker Museum, there are twenty-four presacrals, and it seems improbable that more than one more was present. Nothing can be added to the descriptions of the arches, spines, and zygapophyses. There is little variation down the column, the only noticeable difference between vertebrae being a continuous diminution in the length of the transverse processes as the sacrum is approached. The normally exposed surfaces of the hypocentra are much as Williston and Cope described them. The anterior four have a less extensive ventral surface than do the suc-

ceeding ones. One point of interest is that the hypocentra in all specimens of *Trematops* which have been studied have complete ossification above the notochordal opening, a condition unusual in rhachitomous forms. This condition exists even in forms which otherwise appear to be immature. In no case has this complete ossification been found in specimens of *Acheloma*. It appears to be a distinct difference between the two genera.

Very few caudal vertebrae have been found, and little can be said about them. Nothing is known of the length of the tail, but the supposition is that it was rather long.

Ribs.—No new data concerning the ribs have been obtained.

Humerus.—Williston's description of the humerus applies to all members of the family, the principal variations between species being those of size and degree of ossification. In the specimen which he described, however, the proximal, outer portion of the bone was missing. This area is well preserved in a number of specimens found subsequently. The deltopectoral crest is very strongly developed, and the areas of insertion of the deltoid and pectoral muscles are separate. The anterior dorsoventral line is marked by a strong ridge for the insertion of the brachiohumeralis. An entepicondylar foramen has been described in the humerus of *A. cummınsi*, but, as Case and others have pointed out, this opening is quite surely accidental, occurring as it does only in the left humerus. It is not present in any other specimen of *Acheloma*.

Radius.—The distal and proximal ends of two radii are present in W.M. 1756. The head of the bone is roughly triangular, while the distal end is expanded and rather flat. The exact length of the elements in various forms remains uncertain.

Ulna.—The ulna does not vary much from that of *T. milleri* described by Williston. The proportional length of the bone is slightly less than he indicated. In most specimens the olecranon is not well developed, but in a few very mature individuals it is strongly ossified as shown in Figure 11, *F*.

Manus.—All the elements of the carpus are preserved in the right forefoot of W.M. 1756 except for the fourth distal carpal. They were articulated when found, and the positions, sizes, and shapes of the various elements are shown in Figure 11, *G*. In this drawing the

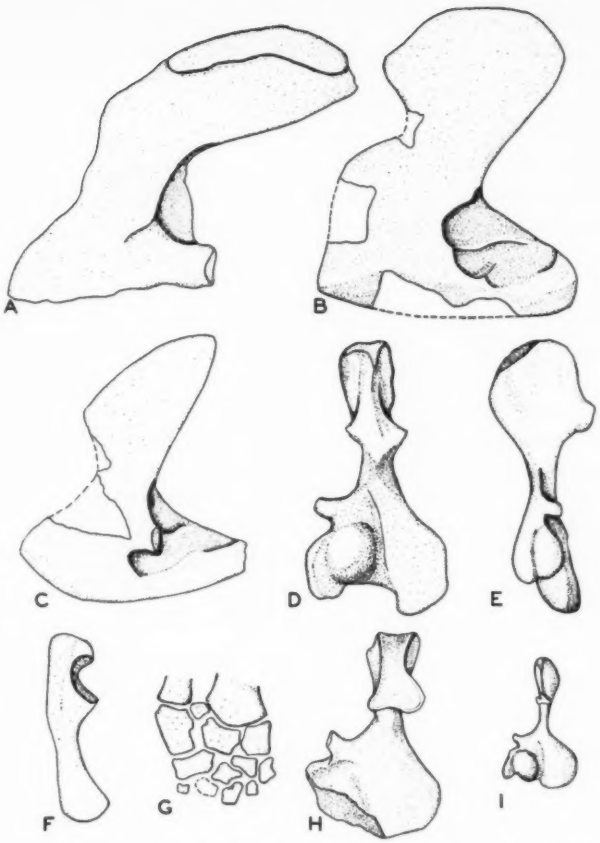

FIG. 11.—Elements of the shoulder girdle and forelimb of *Trematops* and *Acheloma*. *A*, Scapula of *A. ?cumminsi* Cope, M.C.Z. 1413. ×1. *B*, Scapulocoracoid of holotype of *T. milleri*, Williston. W.M. 640. ×½. *C*, Scapulocoracoid of *T. willistoni* n. sp. W.M. 1584. ×1. *D*, Humerus of *T. milleri* Williston. Referred specimen, W.M. 1756. Ventral aspect. ×½. *E*, Same specimen as *D*, anterior aspect. *F*, Ulna of *A. cumminsi* Cope. Referred specimen, M.C.Z. 1490. ×½. *G*, Manus of *T. milleri* Williston. Referred specimen, W.M. 1756. ×½. *H*, Humerus of holotype of *A. cumminsi* Cope, A.M. 4205, ventral aspect. ×½. *I*, Humerus of holotype of *T. willistoni* n. sp. W.M. 1584, ventral aspect. ×½.

fifth distal carpal has been rotated from its position in the specimen to the correct orientation. The positions and proportion of the elements are quite different from those indicated by Williston in his study of the rather poorly preserved forefoot of the holotype of *T. milleri*. The phalanges of the foot are not well preserved in any specimen, and the phalangeal formula is uncertain.

Shoulder girdle.—There is considerable variation in the scapulocoracoid within the family. Two principal types may be differentiated: that of *Trematops*, in which the scapula is erect and dorsally expanded and the coracoid region is well ossified and projected relatively far posteriorly, and that of *Acheloma*, in which the scapula is inflected posteriorly and little expanded dorsally, while the coracoid region is generally poorly ossified and, when developed, is short. It has not been possible to determine the type of scapula in all members of the genus *Acheloma*, and the lack of coracoid ossification in specimens in which the scapula is present makes the true orientation of the scapula somewhat uncertain. The posterior inflection of the scapula does occur in all specimens in which the scapula has been preserved.

The cleithrum is seldom preserved, presumably because the anterior margin of the scapula upon which it rested is generally poorly ossified, permitting the loss of the cleithrum in the course of preservation. The bone is present in M.C.Z. 1413, a specimen of *Acheloma*. In this specimen it is a slender element which covers about two-thirds of the anterior margin of the scapula as shown in Figure 11, *A*.

Very little additional information concerning the clavicles and interclavicles has been obtained. The clavicles, when fully preserved, are somewhat larger than indicated by Williston, and, contrary to his opinion, the ventral surface is pitted. The lack of this character in the holotype of *T. milleri* seems to be the result of the type of preservation, which required removal of the surface of the bone in the process of preparation.

Femur.—Mature femora correspond closely to Williston's description of the femur in *Trematops*. In many specimens, however, ossification of this element is quite incomplete, and the femora present a very different appearance. Ossification of the element in *Acheloma* is usually poor, the head and distal condylar positions generally being

absent. In one specimen of *Acheloma*, M.C.Z. 1549, the femur is complete. This bone is larger than any known in *Trematops*, and,

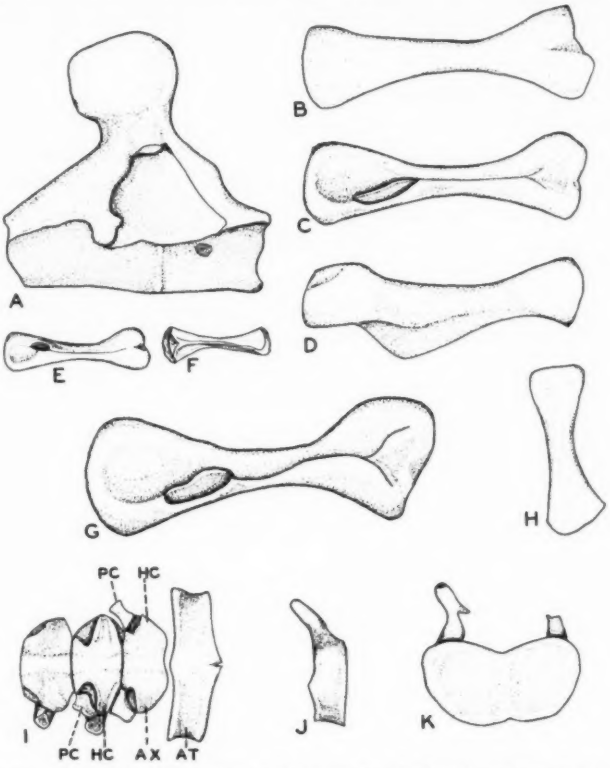

FIG. 12.—*A*, Pelvis of *Trematops milleri* Williston. Referred specimen, W.M. 1756. Lateral aspect. ×½. *B*, Femur of *T. milleri* Williston, same specimen as *A*, dorsal aspect. ×½. *C*, Same specimen as *B*, ventral aspect. ×½. *D*, Same specimen as *B*, anterior aspect. ×½. *E*, Femur of holotype of *T. willistoni* n. sp., ventral aspect. ×½. *F*, Femur of *A. whitei* n. sp., paratype, ventral aspect. ×½. *G*, Femur of *A. cumminsi* Cope. Referred specimen, M.C.Z. 1549. ×½. *H*, Fibula of *T. milleri* Williston. Referred specimen, W.M. 1756. ×½. *I*, Anterior 4 vertebrae of *T. milleri* Williston, same specimen as *H*, ventral aspect. ×1. *J*, Atlas of *T. milleri* Williston, same specimen as *I*, lateral aspect. ×1. *K*, Same specimen as *J*, anterior aspect. ×1.

although the general shape is like that in *Trematops*, the proximal and distal ends are proportionately heavier (Fig. 10, *B–G*). The fe-

mur of *A. whitei* is very small in proportion to skull size and is very poorly ossified. In specimens of *T. milleri* with the same skull size, the femur is well ossified and considerably larger (compare *E* and *F*, Fig. 11).

Tibia.—No additional data have been obtained concerning the tibia. It is very similar in the two genera.

Fibula.—The head of this element is crescentic with a somewhat concave articular surface and a thin anterior and thick posterior edge. The shaft is slender and oval in cross section. The distal end is broad and flat and has a curved articular surface which meets the large fibulare posteriorly and the intermedium anteriorly.

Pes.—Except for certain differences in proportions of elements, the hind foot is much as described for *T. milleri* by Williston. The hind foot of *Acheloma* remains unknown. A detailed study of the foot is being undertaken by Gregory and by Schaeffer on the basis of new material at the present time.

Pelvic girdle.—The pelvic girdle of *Trematops* and *Acheloma* has never been adequately described, for it is not present in the type of *Acheloma* and is poorly preserved in the type of *Trematops*. The complete pelvis is present in W.M. 1756. The left side is shown in Figure 11, *A*.

No sutures separate the three elements, and their exact limits cannot be determined. The ilium forms the dorsal part of a somewhat triangular acetabulum and rises above it as a blade which is but little expanded. The inner surface is cupped for the reception of the single sacral rib, but there are no irregularities or pits on the surface as there are in *Eryops*. The process for the origin of the extensor caudi lateralis is weakly developed on the posterior margin of the ilium near the base of the blade. The supra-acetabular notch is not strongly developed and lies more dorsally than it does in *Eryops*.

The pubis forms the anterior part of the acetabulum, and its junction with the ischium is marked by a low ridge on the ventrolateral shelf for the origin of the puboischiofemoralis externus. The pubic tuber is strongly developed and directed more dorsally than in *Eryops*. A small obturator foramen pierces the pubis, to emerge on the lateral surface just below the anteroventral corner of the acetabulum.

The ischium carries the posterior part of the acetabulum. At the posteroventral corner of this fossa is a rather strong tuber. The ventral plate of the pubis and ischium is very broad, and the ventral symphysis between the two halves of the girdle is strong.

DISCUSSION

RELATIONSHIPS OF THE FAMILY TREMATOPSIDAE

The members of the family Trematopsidae bear resemblances to those of the family Eryopidae and the family Dissorophidae and appear to lie closer to the latter. Certain specific differences between the Trematopsidae and Dissorophidae exist. The former lacks any dermal armor, while the latter possesses a strong series of dermal plates. The skull of the Trematopsidae is proportionately larger and more triangular. No antorbital fossa occurs in the Dissorophidae. Postcranially there are a number of similarities between the two families. In both, the limb bones are long and slender. The femora are quite similar, the principal differences being that the femur of the Dissorophidae has a stronger adductor ridge and is lighter in construction. The radii and fibulae show few differences, but both the ulnae and tibiae of the Dissorophidae are longer and more slender than those of the Trematopsidae. There are no major differences in the pelves. The scapulae of the Dissorophidae are more slender and elongate, and ossification is more complete. The cleithrum is large in the Dissorophidae and small in the Trematopsidae, and the clavicles and interclavicles are much larger in the former. Commonly the coracoid is more strongly developed in mature specimens of the Trematopsidae.

The vertebrae are similar in many respects, the zygapophyses being narrow, the neural spines short, and the transverse processes very strong. The number of presacrals in the Dissorophidae is less than that in the Trematopsidae. There are two sacrals in the former and only one in the latter. It is not known that the hypocentra of the Dissorophidae were ossified dorsally around the notochordal tube as they are in *Trematops*, but it is possible that sectioning of the vertebrae might reveal that this character was developed.

Differences of the skulls in the two families are somewhat greater.

The variation in shape and condition of the preorbital region have been mentioned. The orbits and pineal opening are larger in the Dissorophidae. Closure of the otic notch is accomplished in a different manner in the two families. There is a general similarity of the palates, but in the Dissorophidae the parasphenoid continues forward to make contact with the prevomer and the interpterygoidal vacuities are very large. The shape of the lower jaw is similar in the two families. There are only minor differences in dentition.

These comparisons show that the two families are similar in many respects but different in certain fundamental features. They do not necessarily indicate the degree of proximity to a common ancestor, for all the common characters are either adaptive in nature or reflections of certain general trends in the development of the rhachitomous amphibians. Much of the resemblance may be due to parallelism.

Comparisons of the family Trematopsidae and the family Eryopidae show greater differences. The condition of the otic notch is very different, the notch being shallow in *Eryops* and very deep in *Trematops* and *Acheloma*. The orbits in *Eryops* are more posterior and relatively much smaller. That this is not a character connected with growth is indicated by the condition in some very young specimens of *Eryops* recently obtained. There are decided differences in the palate, and in this region the Eryopidae and Dissorophidae are more similar to each other than is either family to the Trematopsidae.

The principal postcranial differences between the Eryopidae and Trematopsidae are those of proportion, and a number of these may be related to the pronounced difference in size between the members of the two families. The elements of *Eryops* are proportionately shorter and heavier than those of either *Trematops* or *Acheloma*. Muscle attachments are more strongly developed in *Eryops*. The vertebrae differ considerably, those of *Eryops* having proportionately longer neural spines, shorter transverse processes, and broader zygapophyses. The scapula, cleithrum, and clavicale of *Eryops* are proportionately larger and heavier, but the coracoid region is less extensively developed. The ilium of *Eryops* is proportionately much

higher and more slender and has a stronger process for the extensor caudi lateralis. There are minor differences in the pubis and ischium. The basic pattern of the limb bones in the two families is the same, but the various elements are proportionately shorter and heavier in the Eryopidae. The most obvious differences are to be found in the humeri and femora.

Other families of rhachitomous amphibians are less closely related to the Trematopsidae. The Trimerorhachidae are apparently not very closely related but are of interest in that their adaptations are somewhat similar to those of some members of the genus *Acheloma*. The small limbs and poor ossification are quite similar in kind to those of *A. whitei*.

HABITS OF THE TREMATOPSIDAE

All members of the family appear to have been carnivorous or insectivorous. Members of the genus *Trematops* probably were among the most active terrestrial amphibians of their time. The whole skeleton is lightly built, the muscle scars are not heavy, and the articulations of the various elements of the skeleton are well developed. The limb bones are slender and long, much as in some of the contemporary reptiles. Ossification is very complete for an amphibian. Members of the genus *Acheloma* probably spent much of their time in or near the water, except, perhaps, in the cases of very mature specimens. Ossification is seldom complete, and the articulations are poor. Those specimens in which ossification is relatively complete have limb bones which are quite heavy and short. Even in these specimens ossification of the hypocentra is incomplete. Although the two genera are clearly very closely related, it would appear that their habits were dissimilar.

ACKNOWLEDGMENTS.—Dr. Romer, of Harvard, has loaned the writer all the material in the possession of the Museum of Comparative Zoölogy so that as complete a study of known material as possible might be undertaken. The holotype of *A. cumminsi* Cope has been made available for this work by the American Museum of Natural History, New York. Only the specimens of *?A. casei* Broili and *T. thomasi* Mehl have not been studied firsthand. I wish to express my appreciation to those who have been so kind as to make this material available to me.

ABBREVIATIONS FOR FIGURES

ANG.	angular
ART.	articular
AT.	atlas
AX.	axis
BO.	basioccipital
BPT.	basipterygoid process
BS.-PAS.	basisphenoid-parasphenoid
D.	dentary
EO.	exoccipital
EPT.	epipterygoid
FM.	foramen magnum
FOV.	fenestra ovalis
F. PIN.	pineal foramen
FR.	frontal
HC.	hypocentrum
INA.	internal naris
IP.	interparietal
I. PRO.	pro-otic incisure
JU.	jugal
LA.	lacrimal
MX.	maxillary
NA.	nasal
ORB.	orbit
PA.	parietal
PAL.	palatine
PAS.	parasphenoid
PC.	pleurocentrum
PF.	prefrontal
PL.	pleurosphenoid
PMX.	premaxillary
PO.	postorbital
P. PAR.	paroccipital process
PRO.	pro-otic
P. ST.	stapedial process of quadrate
PT.	pterygoid
PV.	prevomer
QJ.	quadratojugal
QU.	quadrate
SANG.	surangular
SO.	supraoccipital
SPETH.	sphenethmoid
SPL.	splenial
SQ.	squamosal
ST.	stapes
STE.	supratemporal
VEST.	vestibule

COMMENTS ON RETROGRADE METAMORPHISM

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ABSTRACT

The theory of retrograde metamorphism as first outlined by Becke and later elaborated by Harker probably is not adequate to explain the mineral changes which have been repeatedly cited as retrograde. This inadequacy is discussed, and a broader definition of retrograde metamorphism, not involving theoretical causes and processes, is proposed.

INTRODUCTION

"Retrograde metamorphism," "retrogressive metamorphism," "regressive metamorphism," and "diaphthoresis" are terms which are being used with increasing frequency, especially since A. Harker[1] devoted a brief chapter to this subject in his text on metamorphism. In many, if not in most instances, however, these terms are not being used in precise accordance with their original connotation. Nor do the various writers state definitely their conception of exactly what processes should be included under the heading "retrograde metamorphism." This, of course, causes much confusion in the mind of the critical reader.

The theory of retrograde metamorphism was first conceived by F. Becke[2] in 1909 to explain the derivation or origin of a group of Alpine phyllites containing minerals which he considered to be characteristically low grade, or epizone, in association with other minerals which he believed should be restricted in occurrence to higher-grade metamorphic rocks. It was Becke's contention that these phyllites had formed from gneisses of the deep-seated zones of the earth's crust as the result of a reversal of normal, progressive, regional metamorphism. To these rocks he applied the term "diaphthorites" (*Greek:* "to degrade").

[1] *Metamorphism* (London: Methuen & Co., 1939), pp. 344–58.

[2] "Über Diaphthorite," *Tschermaks mineralogische petrographische Mitteilung*, Vol. XXVIII (1909), pp. 369–75.

Harker, who has elaborated Becke's original hypothesis, also speaks of retrograde metamorphism as a reversal or partial reversal of metamorphism proper. His treatment clearly indicates that in thermally metamorphosed rocks he conceives of a decline in temperature as the important factor which disturbs the equilibrium of the mineral assemblage and causes retrogression, while in the case of regionally metamorphosed rocks not only a fall in temperature but variations in pressure conditions are responsible for the change.

Even a casual study of the so-called retrograde changes serves to show that the process is by no means simple and that ascribing the changes mainly to a decrease in temperature or changing pressure conditions leads to misconceptions. This is especially true in view of the fact that the term retrograde is often being used in a broader sense at the present time.

In this paper some aspects of retrograde metamorphism will be discussed, and it will be shown that theory, fact, and usage are not in good accord. The possible significance of hydrothermal activity in retrograde metamorphism has often been overlooked but is particularly emphasized in the present discussion. Finally a broader definition is suggested which, it is hoped, will be more adequate.

BASIS OF THE THEORY

Petrologists of many countries have shown that metamorphism often follows an orderly scheme, as a result of which rocks of given composition, under given conditions of temperature and pressure, assume characteristic and recognizable forms. Shale, for example, is converted first into argillite and then into slate when subjected to the forces of regional metamorphism. The slate in turn is converted into a fine-grained phyllite which becomes more coarsely crystalline and passes over into a low-grade schist as the temperature continues to rise. If conditions of temperature and pressure are intense enough to warrant, this low-grade, or epizone, schist may then be changed to a higher-grade schist or gneiss, rocks stable in the more intense mesozone and katazone environments. In this way a low-grade metamorphic rock responding to profound changes in its physical environment alters to a higher-grade type which will mineralogically and structurally be more nearly in equilibrium with the conditions

obtaining. Such is the normal course of progressive regional metamorphism, controlled by a steady increase in temperature and pressure.

The theory of retrograde metamorphism is based on the assumption that metamorphic rocks are also forced to respond to the reversal of these dynamothermal conditions which follows the climax of progressive metamorphism. It has been claimed that, just as a phyllite may alter to a gneiss if subjected to conditions of intense regional metamorphism, a gneiss may climb back down the metamorphic ladder when the temperature falls and pressure is released. Similarly it is claimed that a mineral assemblage resulting from simple thermal metamorphism can be disturbed by mere decline in temperature, not complicated by the pressure factor. In each case retrograde metamorphism consists essentially in a reversal of progressive metamorphism, thermal or dynamothermal.

MINERAL CHANGES

The following mineral changes have been attributed by various writers to retrograde metamorphism:

Actinolite	Clinochlore or antigorite
Andalusite	Sericite or muscovite
Andradite	Epidote
Biotite	Chlorite and magnetite
Cordierite	Chlorite and sericite or muscovite
Corundum	Diaspore or margarite
Diopside	Tremolite or actinolite
Forsterite	Serpentine
Garnet	Biotite or chlorite
Grossularite	Idocrase, zoisite, or clinozoisite
Hornblende	Biotite, chlorite, or serpentine
Ilmenite	Leucoxene
Kyanite	Sericite or muscovite
Periclase	Brucite
Plagioclase	Zoisite
Potash feldspars	Sericite
Sillimanite	Sericite or muscovite
Sillimanite+biotite+H_2O	Staurolite and muscovite
Staurolite	Chloritoid or muscovite
Wollastonite	Calcite

A striking fact regarding this list of mineral changes is that many of them represent extensive hydration and that minerals are produced which are characteristic of hydrothermal alteration.[3] This raises the question as to whether or not changes in metamorphic rocks resulting from the activity of hydrothermal solutions are to be included in retrograde metamorphism. Considered independently of any theory, it is evident that hydrothermal changes are often retrogressive or destructive in nature and should be included.

Such changes have been called retrograde by several workers. M. P. Billings,[4] for example, has stated that the schists of New Hampshire probably did not contain sufficient water for the formation of the abundant retrograde minerals of that region and suggests that water was introduced from external sources. K. Preclik[5] emphasized the necessity of mineralizers in diaphthoresis.

The change from biotite to chlorite is one often cited as a retrograde change. This requires abundant water, as shown by the following comparison:

Biotite	Chlorite
$K_2(OH)_4(Mg, Fe)_6(AlSi_3O_{10})_2$	$(OH)_{16}Al_4Mg_{10}Si_6O_{20}$.
H_2O = 4.5 per cent	H_2O = 12.9 per cent

Presumably the potash of the biotite forms sericite with approximately the same percentage of water as biotite. Several other mineral changes listed above show an equally striking change in H_2O content. Forsterite to serpentine requires the addition of 12.9 per cent H_2O. Hornblende contains about 1.5 per cent H_2O as compared with chlorite's 12.9 per cent. Periclase, with no H_2O, is reported to alter to brucite, which contains 31 per cent H_2O. Other appreciable increases in H_2O content will be noted in the list of mineral changes.

[3] G. M. Schwartz, "Hydrothermal Alteration of Igneous Rocks," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp. 181–238.

[4] "Regional Metamorphism of the Littleton-Moosilauke Area, New Hampshire," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), pp. 463–566.

[5] "Zur Genesis einiger Moldanübischer Gesteintypen I.," *Centralbl. für Min. u. Pal. Abt. A 61–78* (1930).

Harker states that as a result of degradation some calcite may be produced at the expense of wollastonite. This would obviously require the introduction of CO_2, which might take place as a hydrothermal effect.[6]

Since the above paragraph was written, N. L. Bowen's[7] paper on progressive metamorphism of carbonate rocks has appeared. His statement regarding CO_2 in retrogressive metamorphism is similar to the above argument regarding H_2O. Bowen believes that the CO_2 is eliminated during metamorphism and that the minute amount which remains in the pores is inadequate for retrogression. Therefore, when calcite or dolomite is formed during retrogression, CO_2 must have been supplied. Bowen suggests the possible source of this CO_2.

W. M. Agar[8] has described an example in which common contact-metamorphic silicates are diopside, tremolite, scapolite, and phlogopite. The hydrous minerals—serpentine, talc, and chlorite—have formed at the expense of earlier silicates. An example of required extensive hydration is furnished by F. J. Turner,[9] who states that high-grade schists in New Zealand have been subject to retrogressive metamorphism with chloritization of biotite, sericitization of feldspar, cordierite, and andalusite, and the alteration of ilmenite to leucoxene as the important mineral changes.

Harker emphasizes sericitization of the aluminous silicates of contact hornfels. Sericitization is a process generally associated with hydrothermal conditions. If decreasing temperature alone was sufficient to cause sericitization of potash feldspar in hornfels, it is difficult to explain why the same thing does not happen in igneous rocks. Why should a metamorphic rock be under more active chemical conditions than an igneous rock during the fall in temperature?

[6] Schwartz, *op. cit.*, p. 229.

[7] "Progressive Metamorphism of Siliceous Limestone and Dolomite," *Jour. Geol.*, Vol. XLVIII (1940), pp. 225–74.

[8] "Contact Metamorphism in the Western Adirondacks," *Proc. Amer. Phil. Soc.*, Vol. LXII (1923), p. 103.

[9] "Progressive Regional Metamorphism in Southern New Zealand," *Geol. Mag.*, Vol. LXXV (1938), pp. 160–74.

DISCUSSION

It is evident that in practice hydrothermal alteration has not been entirely excluded from retrograde metamorphism. Throughout much of the general discussion of theory, on the other hand, little mention is made of hydrothermal conditions; rather, there is a tendency to treat the process of retrograde metamorphism as taking place essentially in a closed system with much emphasis placed on the fall in temperature. The fact that retrograde metamorphism is an uncommon effect is recognized by most, if not all, writers. The failure of the minerals to react to the new conditions of equilibrium is said to be due to the fact that reactions are greatly retarded by falling temperature. That chemical reactions are retarded by falling temperature is a well-established fact, but the time factor must not be ignored. In nearly all metamorphism temperature changes are exceedingly slow, whether rising or falling, and a great deal of time is available for the attainment of equilibrium before the temperature could fall even a few degrees below the point at which the minerals become metastable. It seems permissible, therefore, to question the validity of the general statement that temperatures drop so rapidly as to greatly inhibit retrograde reactions. It seems more likely that the failure to react is due to the absence of some essential component rather than merely to temperature conditions.

Both A. Kieslinger[10] and E. B. Knopf[11] have suggested that evidence of retrograde metamorphism is not more widespread because it is recognizable only when the transformation is incomplete, and that it is probably a much more common phenomenon than the amount of evidence might indicate. Knopf further suggests the probability that petrographers have erroneously been describing many phyllites and schists as low-grade metamorphic rocks, while in reality they are diaphthorites. In her discussion of phyllonitization she states that a completely retrogressed phyllite is not distinguishable except possibly by field relationships. It does not appear reasonable, however, to assume that a diaphthorite should re-

[10] "Geologie und Petrographie der Koralpe, I," *Wien. Akad. Sitzber., math.-naturw. Kl.*, Vol. CXXXV, No. 1 (1926), p. 8.

[11] Knopf, E. B., "Retrogressive Metamorphism and Phyllonitization," *Amer. Jour. Sci.*, Vol. XXI (5th ser., 1931), pp. 1–27.

tain none of its characteristics, especially when complete retrogression is admittedly uncommon. The very argument used to explain why retrogression is uncommon can also be used to argue that evidence of retrogression should remain. It seems scarcely logical to use the argument about inhibitions and then to ignore its implications. The following statement by Billings, who has for several years been conducting a detailed study of regional metamorphism in New Hampshire, one of the important localities for so-called retrograde metamorphism, is of great significance in this connection:

> The more intense types of retrograde metamorphism discussed by E. B. Knopf, such as the conversion of middle-grade and high-grade rocks into phyllonites with a typically low-grade appearance and mineral assemblage, have not been observed. There is no evidence that the retrograde processes already described bear any relation to special structural features, such as thrust faults; rather, the retrograde minerals appear sporadically throughout the area.[12]

A. Demay,[13] describing the petrography of the central batholith region in France, reports the discovery of many "diaphthoritic rocks" but no true "diaphthorites."

It has been stated in the literature that mineralogical criteria furnish the only conclusive proof of retrogression. Precisely what these criteria are is not clear, but certainly the list of mineral changes, such as garnet and biotite to chlorite, feldspar to sericite and zoisite, cannot be considered positive criteria of retrogression unless hydrothermal changes are recognized as being an essential part of retrogression. The alterations noted are certainly very common products of hydrothermal activity.[14]

The fact that many so-called retrogressive mineral changes are identical with those which have long been recognized as typical hydrothermal effects is highly significant. It is significant because these changes can probably be explained more convincingly in terms of hydrothermal alteration than they can by any theory which emphasizes a decline in temperature (and, in the case of regionally

[12] Billings, *op. cit.*

[13] "Sur le métamorphisme régressif ou diaphthorèse dans le massif central," *Soc. géol. France, C.R. 10* (1927), pp. 117–19.

[14] F. F. Grout, *Petrography and Petrology* (McGraw-Hill Book Co., Inc., 1932), p. 426.

metamorphosed rocks, release of pressure), almost to the exclusion of other factors. Such hydrothermal alteration may or may not take place during the fall in temperature following metamorphism. In some cases igneous intrusions, long after the period of original metamorphism, may set up hydrothermal conditions capable of promoting "retrograde" reactions.

In most, if not in all, areas from which evidence of retrograde metamorphism has been reported there is also evidence of widespread hydrothermal or even pneumatolytic activity. G. W. Tyrrell,[15] for example, offers the following evidence: "The widespread occurrence of tourmaline in the schists of the Scottish Highlands, even in areas remote from the granite masses which intersect these rocks, points to their thorough permeation by boric acid vapors." The schists of New Hampshire are cut by an abundance of pegmatites and igneous intrusives which clearly were emplaced after the area was subjected to regional metamorphism. The metamorphic rocks of the region were without doubt greatly affected by solutions released from these magmas.

It has already been stated that retrograde changes, when found, were rarely complete. C. A. Chapman[16] noted that the alteration of large metacrysts of garnet and staurolite in the schists of New Hampshire was complete only in the case of badly fractured crystals and that the alteration was generally from the outside inward. This again suggests that the alteration of these metacrysts is due primarily to the attack of hydrothermal solutions and that the work of these solutions was complete only where fractures enabled the solutions to attack the entire crystal. "Armored relicts," described by other writers, appear to be identical with those partially altered crystals which Chapman discusses. Therefore it is suggested that the "lag effect" to which reference is commonly made is often no more than an indication of incomplete hydrothermal alteration.

In addition to the mineralogical changes already listed, Harker cites certain microstructural rearrangements which may result from,

[15] *Principles of Petrology* (E. P. Dutton & Co., 1937), p. 253.

[16] "Geology of the Mascoma Quadrangle, New Hampshire," *Bull. Geol. Soc. Amer.*, Vol. L (1939), p. 175.

and serve as evidence of, retrograde metamorphism. Corrugations modifying the schistosity of phyllites, for example, are mentioned. That these may develop during the late stages of metamorphism is not denied, but they may also result from movements during a later period of deformation. In any event, such corrugations could scarcely serve as criteria for the recognition of retrograde metamorphism.

Nor can the observation that some of the minerals in metamorphic rocks are fractured while others show no signs of deformation serve as a more conclusive criterion. Harker says: "The point to be especially noted is that these products of high-grade metamorphism are often seen broken and displaced, while micas, tourmaline, magnetite, sodic feldspars, and quartz in the same rock seem to have been immune from attack." The interpretation that Harker fails to suggest is that these untouched and undeformed minerals were quite possibly formed after the others had been crushed by the stress to which they were subjected. Such an interpretation seems to be suggested by Harker's own observation that these minerals have filled fissures in high-grade minerals and molded themselves upon the broken surfaces.

Billings notes that in New Hampshire no evidence could be found to indicate any relationship whatever between retrograde metamorphism and the thrust faults or other special structures of the region.

The very fact that retrograde reactions are uncommon seems convincing evidence that retrograde changes cannot be attributed mainly to a lowering of temperature or changes in pressure conditions. On the other hand, it is widely recognized that these mineral changes can be effected by hydrothermal solutions. The increase in H_2O and the addition or subtraction of other mineral-forming molecules, such as K_2O, involved in the majority of these changes, combined with the important observation that the reactions are rarely complete and that the alteration of the affected crystals has been from the outside inward and has followed fractures in the crystals, indicate that the alterations have been promoted chiefly by metasomatism and the action of hot-water solutions. In other words, it is the thesis of this paper that at least many of the so-called retrograde mineral changes

in both thermally and regionally metamorphosed rocks are due to hydrothermal action.

There are several indications in the literature that this idea has been in the minds of other investigators. T. F. W. Barth expresses the idea in his paper on the metamorphic rocks of Dutchess County, New York. He says:

> Obviously most rocks have been subjected to the conditions of lower mineral facies than those of their present mineral assemblage. But they have not responded to the change of environment. Why? The answer seems to be that all reactions at these temperatures are so slow as to preserve the initial mineral facies indefinitely. The rocks need a catalyst in order to change to a lower facies. Such catalysts are the hydrothermal solutions which act not only catalytically but also metasomatically, so as to change the bulk composition of the rock, through replacement of the old minerals by new and different minerals.[17]

Reference has previously been made to Billings' suggestion that water was probably introduced before retrogression in the schists of New Hampshire was possible.

Thermal, as noted in some detail by Harker, is the simplest kind of metamorphism which may be followed by retrograde metamorphism. Contact metamorphism, however, is often not simple thermal metamorphism, the variety principally discussed by Harker. V. M. Goldschmidt[18] has emphasized the two phases of contact metamorphism, an inner zone of higher temperature and mainly recrystallization and an outer zone—believed by Goldschmidt to be later in formation—marked by the introduction of H_2O and other mineralizers and often metallic elements.

The effect of late emanations on the inner-contact silicate zone must be essentially retrogressive. J. Barrell[19] emphasized that at Marysville hornblende of the contact zone altered to biotite by hydrothermal metasomatism and biotite to chlorite by hydrous metamorphism. The literature on contact metamorphism contains numerous other examples of hydrous minerals which have formed

[17] "Structural and Petrologic Studies in Dutchess County, New York," *Bull. Geol. Soc. Amer.*, Vol. XLVII (1936), p. 844.

[18] "Die Kontaktmetamorphose im Kristianiagebiet," *Vidensk. Skr. Kristiania, 1911, I. Mat.-Naturv. Klasse*, Band I (1912), pp. 211–20.

[19] "Geology of the Marysville Mining District, Montana," *U.S. Geol. Surv. Prof. Paper 57* (1907).

during the later stage at the expense of anhydrous minerals of the earlier stage.

J. L. Gillson[20] recognized three stages in the contact metamorphism of calcareous rocks in the Pend Oreille district of Idaho. The usual contact silicates formed during the second stage, sericite and chlorite during the third. This is clearly a retrogressive change but is due chiefly to the activity of hydrothermal solutions rather than to a simple fall in temperature. It is the outer and later stage emphasized by Goldschmidt and by Barrell.

Probably the most critical point in the evaluation of retrograde metamorphism is the amount of change in chemical composition. It has been stated that the small amount of water necessary for some retrograde changes remains in the metamorphic rock. How or why it remains is not stated, nor does any good reason for such an assumption appear. Why should CO_2, for example, be expelled and H_2O remain? It seems more reasonable to assume that H_2O is expelled during metamorphism; and, where retrogression occurs, it is supplied along with other substances to the rock by solutions emanating from igneous rocks. Other chemical changes are also important. Harker states that the introduction of material necessary for some retrograde changes, for example, potash, is inadmissible. This statement seems insupportable in view of the numerous well-established examples of the introduction of potash during the alteration of many rocks.

Chemical changes were recognized by Becke, who states that a gain in K_2O and a loss in SiO_2, CaO, MgO, and Na_2O were shown by the retrograde rocks he examined. It is difficult to imagine how such changes could occur unless solutions were active.

DEFINITION

Because of the rather obvious difficulties involved in the use of the term "retrograde metamorphism" as it has been defined in the past, a more general definition seems to be desirable. It is suggested that the definition of retrograde metamorphism be divorced from theories as to its cause and that the idea of a change of a metamorphic

[20] "Contact Metamorphism of the Rocks in the Pend Oreille District, Northern Idaho," *U.S. Geol. Surv. Prof. Paper 158* (1929).

mineral or metamorphic rock to that of a probably lower grade be the main requirement. Thus no assumption regarding the time of alteration will be involved, and theoretical ideas regarding falling temperatures and changing pressure conditions as the sole or even prime causes will also be eliminated.

Retrograde metamorphism, then, may be defined as any change not caused by weathering, by which a metamorphic mineral or metamorphic rock of a so-called higher grade alters to a mineral or rock of lower grade, i.e., to minerals and rocks more stable at lower temperatures and pressures and containing more water.

SUMMARY

Certain mineral changes (see p. 179) have repeatedly been attributed to a highly theoretical process of retrograde metamorphism, which, according to original definition, consists essentially in a reversal or partial reversal of progressive metamorphism, thermal or dynamothermal (regional). In other words, these mineral changes have been attributed to a decline in temperature following thermal metamorphism, or a decline in temperature combined with a lessening of pressure following regional metamorphism. This is in spite of the fact that it is widely recognized that large amounts of water, as well as smaller amounts of other substances, are essential to these mineral changes. Harker and others have, however, rather clearly excluded true hydrothermal conditions from their definitions and discussions of retrograde metamorphism. It is the thesis of this paper that hydrothermal alteration is by its very nature a so-called retrogressive effect if it attacks metamorphic rocks which formed in the deeper zones, i.e., high-grade metamorphic rocks.

The following observations suggest that retrogression is due chiefly to the attack of hydrothermal solutions on so-called high-grade metamorphic minerals:

1. Retrogressive mineral changes require large amounts of H_2O. The change from pyroxene → amphibole → biotite → chlorite serves as an excellent example. Often the addition or subtraction of some other substance is also necessary.

2. The mineral changes are similar to those which have been regarded as characteristically hydrothermal.

3. Evidence of widespread retrograde alteration is the exception rather than the rule.

4. Retrograde alteration is rarely, if ever, complete.

5. Crystals retrogress from the outside inward, and the alteration generally follows fractures in the crystals.

6. Regions in which evidence of retrograde metamorphism is found are regions which are known to have been subjected to widespread igneous activity and therefore, in all probability, to the action of hydrothermal solutions.

It is suggested that, in order to avoid confusion in the future, the term "retrograde" and its synonyms be divorced from all theory regarding the cause of retrogression and be used with reference to any metamorphic mineral which apparently has been formed at the expense of a higher-grade metamorphic mineral.

ACKNOWLEDGMENTS.—The writers are indebted to Professor Frank F. Grout for suggestions and criticisms.

METASOMATISM OF A COALY SEDIMENT INTO AN IGNEOUS-APPEARING ROCK[1]

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ABSTRACT

In the southeastern portion of Mount Rainier National Park seams of lignitic material occur locally in a thick series of arkosic sandstones and shales which can probably be correlated with the Puget series of the Eocene. Some members of this series, however, have been so altered by low-temperature metasomatic replacement that they resemble portions of the Keechelus andesitic series of the Miocene as described by Smith and Calkins in the Snoqualmie folio. This type of metamorphism is especially well developed in the incompetent carbonaceous material which is replaced locally by a fine-grained, igneous-appearing dacitic groundmass containing porphyroblasts of quartz and plagioclase.

INTRODUCTION

At a number of localities in western Washington dacitic and rhyolitic rocks show gradational contacts with sedimentary rocks and are associated with replacement breccias. Recent road cuts near the southeastern Ohanapecosh entrance of Mount Rainier National Park have exposed several spectacular contacts, including some with coal seams. Without the evidence of these contacts and from a casual inspection alone, all these rocks of apparent volcanic origin would be interpreted as having been formed by the consolidation of lavas or magmas.

Along the new road leading north from the park entrance are exposed a series of well-stratified shales, arkoses, and conglomerates, with associated volcanic breccias and local interbedded coal seams. This series, which dips eastward at angles from 20° to 40°, is presumably part of the coal-bearing Puget group which farther west has been established as Eocene. The stratigraphy of this extensive group, which is well exposed in the Puget Sound region, has been studied in considerable detail by Charles E. Weaver.[2] The nearest

[1] Presented at the December, 1937, meeting of the Geological Society of America at Washington, D.C., under the title "Transformation of a Carbonaceous Sediment."

[2] "Tertiary Stratigraphy of Western Washington and Northwestern Oregon," *Univ. of Wash. Pub. Geol.*, Vol. IV (June, 1937), p. 270.

known fossiliferous locality, however, is a 10,000-foot section on the west side of Mount Rainier, approximately 30 miles northwest of Ohanapecosh.

The relations between the Puget group and the lower portion of the Keechelus andesitic series is very obscure. In the Snoqualmie area 40 miles to the north of Ohanapecosh, G. O. Smith and F. C. Calkins[3] described the Keechelus as a series composed principally of fragmental rocks, andesitic flows, and subordinate amounts of dacite, rhyolite, and basalt. They state in their description of the formation, however, that "in their larger exposures the tuffs and lavas display distinct bedding, and some of the finer layers show the effect of water sorting and resemble ordinary shale and sandstone." They also observed that the series locally grades into pyroxene diorites, which they considered to represent the "roots of the volcanoes" from which the andesitic flows were erupted. Only in the upper part of this heterogeneous series is the occurrence of definite flows established.

Later work has added to our knowledge of the Keechelus andesitic series in the Snoqualmie region. It is now known that it covers thousands of square miles in the Cascades of Washington and has an average exposed thickness of about 2,000 feet.[4] Recent petrologic work in limited areas of the lower Keechelus warrants, in the opinion of the writers, the suggestions that some of the breccias, seemingly igneous, have resulted from the metamorphism of sedimentary rock. Numerous feldspar crystals in the sedimentary rock are definitely porphyroblasts. The concentrated development of these crystals along fractures and in scattered patches produced a rock which has been termed a replacement breccia.[5]

Although not exposed in the Ohanapecosh district, a granodiorite batholith called the Snoqualmie granodiorite by Smith and Calkins and considered to be of late Miocene age has invaded these rocks at

[3] "Snoqualmie Folio," *U.S. Geol. Surv., Atlas 139* (1906), pp. 1–14.

[4] Howard A. Coombs, "The Geology of Mt. Rainier National Park," *Univ. of Wash. Pub. Geol.*, Vol. III, No. 2 (July, 1936), pp. 131–212; "Mount Baker, a Cascade Volcano," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp. 1492–1510.

[5] G. E. Goodspeed and Howard A. Coombs, "Replacement Breccias of the Lower Keechelus," *Amer. Jour. Sci.*, Vol. XXXIV (1937), pp. 12–23.

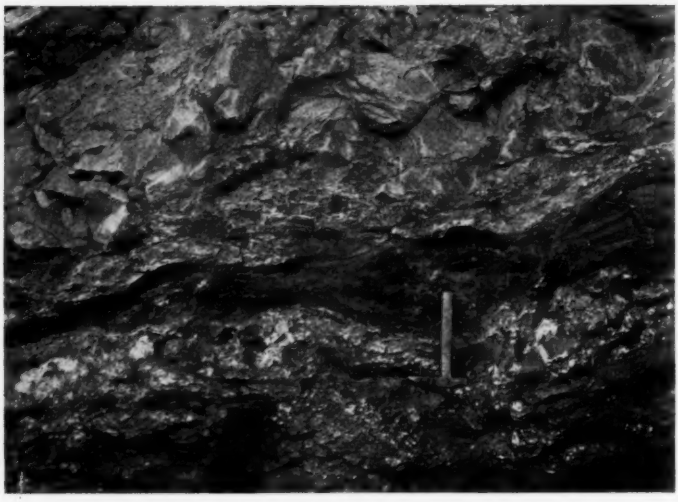


FIG. 1.—Partially deformed coal seam in sedimentary series exposed in road cut north of Ohanapecosh.

FIG. 2.—Detail of Fig. 1 showing the relation of coal to the light masses and the dacitic matrix that occurs adjacent to the coal.

several localities. One of the closest outcrops of granodiorite is in the Tatoosh Range, 10 miles to the west, and another near Chinook Pass, 16 miles to the northeast of Ohanapecosh. Hot springs of undetermined origin occur at Ohanapecosh within 2 miles of the area here discussed, while 12 miles to the north the crater of Mount Rainier still shows a slight amount of fumarolic activity.

COALY MATERIAL

At Ohanapecosh coaly material occurs in the sedimentary series in narrow seams which vary in width from a fraction of an inch to a

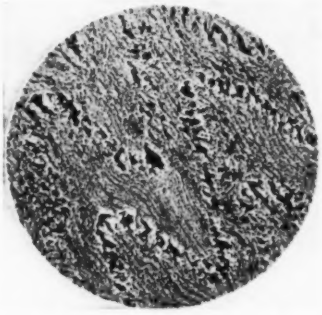
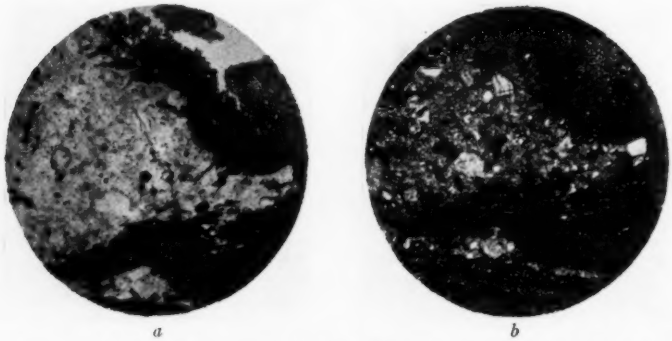


FIG. 3.—Thin section of coal showing cell structure deformed by pressure and partially destroyed by the crystallization of quartz and feldspar. Field of view 1 mm in diameter.

foot or more (Fig. 1). These variations are due principally to minor deformation of the incompetent beds. Locally these beds are brecciated. In the sedimentary rock adjacent to the seams are irregular masses of light gray rock which superficially resemble altered fragments of acidic pyroclastic rock (Fig. 2). Intimately intermixed with both the coal and the whitish patches is a quartz-feldspar aggregate having the general megascopic appearance of dacitic lava.

Even adjacent to the contact with this dacitic rock the coal, in thin section, exhibits the cell structure of the wood in spite of deformation and the impregnation of silica (Figs. 3 and 6). Locally, however, the cell structure has been destroyed by the more intensive development of crystallities, presumably of quartz and feldspar, giv-

ing the coal in this section a minutely mottled appearance (Figs. 3 and 4). Some of the contacts are sharp and locally show an inter-



a *b*

FIG. 4.—Thin section of contact of dacitic rock and coal under plane light (*a*) and with crossed nicols (*b*). Note frayed margin of coal, feldspar porphyroblast at apex of embayment on right, adjacent to partially destroyed cell structure and discontinuous veinlet at bottom. Field of view 2.5 mm in diameter.

FIG. 5

FIG. 6

FIG. 5.—Thin section of contact of the dacitic rock and coal showing interfingered relationship controlled by the grain of wood structure. Field of view 2.5 mm in diameter.

FIG. 6.—Thin section of coal with well-preserved cell structure controlling in part the distribution of the igneous-appearing dacitic rock which is present both as veinlets and as small irregular masses that appear to be discontinuous. Field of view 1 mm in diameter.

fingering of the quartz-feldspar aggregate parallel to the grain of the wood (Fig. 5). Many, however, are gradational. Some of these ex-

hibit a minutely frayed margin indicating the original fibrous structure of the wood (Fig. 4). The grain of the wood also controls in part the irregular veinlets of the quartz-feldspar aggregate and its resultant distribution in a succession of small irregular masses which appear locally to be discontinuous (Figs. 4 and 6). Some of the feldspar crystals in the veinlets are elongated in habit and oriented transversely to them; others penetrate the coaly material (Figs. 5

FIG. 7

FIG. 8

FIG. 7.—Thin section of carbonaceous material showing no apparent cell structure but exhibiting porphyroblasts of feldspar both along veinlets and in the carbonaceous material. Field of view 1 mm in diameter.

FIG. 8.—Thin section of the dacitic rock showing relics of coal which locally contain porphyroblasts. Field of view 2.5 mm in diameter.

and 7) and even contain small carbonaceous inclusions. In fact some occur directly in the coal as porphyroblasts (Fig. 7). On the other hand, long, thin, delicate relics of coalified wood, which retain a fine lacelike tracery of cell structure, locally appear undisturbed in the quartz-feldspar aggregate (Fig. 8). Some irregular bituminous streaks, however, indicate the deposition of the mobile products of distillation.

IGNEOUS-APPEARING DACITIC ROCK

Under the microscope the dacitic material exhibits a very fine but uneven texture (Figs. 4 and 9). Plagioclase is the most common constituent showing euhedral tendencies and has two distinct habits. The larger crystals vary from 1 to 4 mm. in length and are extremely

turbid, owing to numerous minute inclusions. These inclusions are so abundant that in ordinary light the crystals blend into the groundmass and can be detected only under crossed nicols (Fig. 4). Some of the plagioclase crystals contain small particles of coal or have a large concentration of coaly material around their borders, as though the force of crystallization had pushed aside the coal. These larger crystals are invariably anhedral to subhedral in form and often have either extremely ragged borders which feather out into the

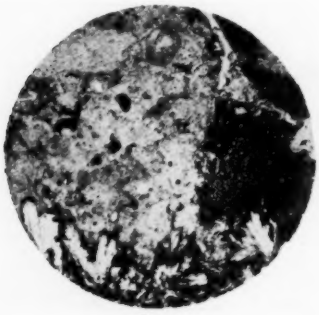


FIG. 9

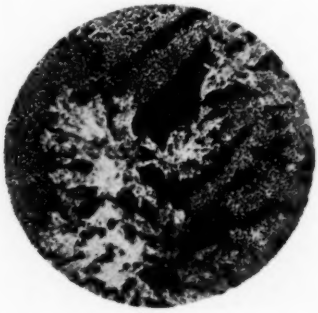


FIG. 10

FIG. 9.—Thin section of the contact of coal and dacitic rock which includes carbonaceous fragments and very turbid porphyroblasts. The plumose mineral is zoisite, which, in the process of growth, has caused the concentration of carbon at the termini of the zoisite crystals. Field of view 2.5 mm in diameter.

FIG. 10.—Thin section of coal in which the cell structure has been largely destroyed, in part by the growth of plumose zoisite. Field of view 1 mm in diameter.

groundmass or long thin extensions of veinlike character (Fig. 9). The smaller crystals are less than 1 mm. in length and grade down to microlite size. Definitely contrasting to the irregular large plagioclases, the smaller ones are crystal clear, and the long thin laths exhibit a perfectly euhedral shape. Both types of plagioclase vary from Ab_{96} to Ab_{82}.

Quartz anhedra are fairly common and ordinarily correspond in size to the larger plagioclases. In the very fine-grained, dominantly siliceous groundmass larger crystals of epidote and zoisite also occur. The epidote is in scattered crystals which are exceedingly ragged. The zoisite, showing a $2V$ of 35°, apparently has grown from

various centers and developed radially somewhat in the fashion of zeolites (Figs. 9 and 10). In so growing, both in the dacitic material and in the coal, it has pushed carbonaceous matter aside and concentrated it, especially on the termini of the crystals (Fig. 10).

INTERPRETATION

Several hypotheses might be advanced to explain the origin of the igneous-appearing dacitic material: (*a*) it might be considered as a silicic lava or magma intruded into the coal-bearing shales; (*b*) another explanation is that it was originally a crystal tuff which has been subsequently altered; (*c*) a third hypothesis is that it was formed by hydrothermal solutions traversing the shale and the coaly material within the shale.

Although superficially the quartz-feldspar aggregate resembles an acidic lava, numerous facts are not in harmony with this explanation of origin. The presence of undecomposed coal indicates a temperature far too low for a magma or lava. Lack of mass flowage is indicated by the survival of delicate inclusions of coalified wood, the absence of flow structure, and the position of crystals. There are no textural changes such as selvages around fragments or along contacts, as might be expected in a melt. No vesicular structures are present. The contemporaneity of minerals like epidote and zoisite with feldspar and quartz would not be expected in an orthomagmatic rock.

The explanation of this quartz-feldspar aggregate as an altered pyroclastic rather than a true volcanic is more plausible, but the occurrence of feldspar crystals within the coal and the inclusion of coaly material in the feldspar both present strong evidence against pyroclastic origin. The form of the contact, with the intergrowth of veinlike occurrences of the igneous-appearing material in the coaly material and with the long, thin, delicate inclusions of coal in the quartz-feldspar aggregate, is not compatible with the deposition of a crystal ash. The lack of any true shards or pumice relics is contributing evidence against the interpretation of pyroclastic origin. The hypothesis, however, is conclusively refuted by the fact that the crystals have pushed aside the coaly material in the process of growth.

Although superficially it may seem strange that a dacitic rock

could be formed by hydrothermal solutions, this interpretation appears to the writers to present by far the best explanation of all the facts. The feldspars show many features indicative of crystalloblastic development, such as their various stages of development from initial, ill-defined forms to fully developed crystals, carbonaceous inclusions, hairline extensions, and gradational as well as sharp boundaries. The inclusion, as well as the pushing aside of coaly material, testifies to porphyroblastic rather than phenocrystic origin. Epidote, zoisite, and zeolites indicate hydrothermal origin, and their contemporaneity with the quartz-feldspar aggregate favors this explanation. Quartz veinlets and an infiltration of silica both in the shale and in the coaly material is most easily accounted for by hydrothermal solutions. Numerous thin sections showing the igneous-appearing material in contact with coaly material or coalified wood indicate that there was a gradual metasomatic replacement of the coal by the quartz-feldspar aggregate. Since coal is present, it is safe to assume that the metasomatic processes were affected by hydrothermal solutions at a comparatively low temperature.

At Ohanapecosh the coal-bearing series has been folded and locally fractured. It would be reasonable to expect that rising hydrothermal solutions would have found a ready pathway adjacent to incompetent coal seams along inclined strata. These solutions may well have been genetically related to the emplacement of the adjacent Snoqualmie batholiths. Here, however, the noteworthy results of these solutions appear to have been the development of igneous-appearing material as well as the metasomatic replacement of coal by this dacitic material. It is also possible that the presence of carbonaceous material accelerated the chemical processes of metasomatism.

ACKNOWLEDGMENTS.—In conclusion the writers wish to acknowledge the co-operation of the National Park Service for the many courtesies extended to them in the course of these studies.

MEASURING GRAIN BOUNDARIES IN CRYSTALLINE ROCKS

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ABSTRACT

Technique for measuring grain perimeters and surfaces in crystalline rocks is outlined. A tabulation of values for the range of crystalline limestones is included as an illustration of measurements. Application of results to determining width of intergranular space and adsorptive capacity is indicated.

INTRODUCTION

Every geologist has observed that the constituent grains of crystalline rocks have either smooth or irregular outlines. It has been evident that length of contact is greater for irregular than for smooth types. However, no coefficient of irregularity for crystalline rocks comparable to that for sediments was recognized; a small radius of curvature at grain points renders sediment-analysis methods inapplicable. Grains of similar size might be compared by the relative lengths of their perimeters, since the more irregular grains have the greater perimeter, but differences in grain size introduce obvious inherent difficulties. This problem of grain irregularity and its measurement barred progress in several lines of study of the crystalline limestones, and its solution seems to open new fields in structural petrology of metamorphic rocks.

The method is simple. Briefly, the length of contact between the grains is measured for a representative area of the rock. Also the number of grains in that area is recorded. The ratio between the length of contact and the square root of the number of grains is the coefficient of irregularity. The average of the coefficients in Table 1 is 1.96. Irregular outlines raise the value and smooth outlines lower it. Rocks might be classed as extremely smooth grained (-1.75), smooth grained (1.75–1.90), average (1.90–1.96), irregular (1.96–2.05), and extremely irregular (over 2.05). The method has been applied to the crystalline limestones and has been verified in the size

range between 75 and 93,000 grains per square centimeter. It is not applicable to rocks containing over 4 per cent of minerals with a conspicuous dimensional elongation. It should be a satisfactory aid to the study of quartzites, most gneisses, and many equigranular igneous rocks.

Recognition of a ratio between length of grain contact and number of grains permits easy estimation of contact area in a given volume by use of the grain count. Area of contact makes possible surface-adsorption studies, width of intergranular space determinations, and investigation of intergranular friction under stress. Statistical comparisons of irregularity coefficients show high irregularity in pre-tectonic marbles and low irregularity in post-tectonic marbles. This is likely to be helpful in directing search for data on geologic history where other lines of investigation have been discouraging.

THE METHOD

The method requires two steps. First, an accurate, enlarged view of a representative area of the rock is necessary. Second, the length of contact between the grains in this enlarged view is determined by running a map measurer once along each contact. Attempts to run a measurer along contacts when the magnification is too low will give experience on the satisfactory size of drawing or photomicrograph and the minimum magnification. Some measurements listed in the table are from sheets 2 feet by 3 feet.

The enlarged view may be obtained by accurate tracing of a projected image, which is very tedious. An easier method is to have a photomicrograph enlarged by projection on a matte paper (glossy paper is unsatisfactory). The petrographic slide should be set to give maximum relief at grain borders; this is the most satisfactory method of bringing out crystal limits, since light-colored prints are easier to use than dark ones obtained by crossed-nicol photomicrographs.

Assuming that an enlarged representation of the rock is available, the task becomes one of measuring all grain contacts and measuring them once only. This is done with a map measurer, the most satis-

factory one having small teeth on the roller point which leave an imprint on matte photographic paper. Suitable placing of the paper with reference to a light will make the teeth marks conspicuous and overrunning a contact avoidable.

TABLE 1

GRAIN-BORDER MEASUREMENTS FOR SOME TYPICAL MARBLES

Type of Marble	Grains per Cm.^{2}	Length of Contact per Cm.^{2}	$\frac{L}{\sqrt{G}}$	Area of Contact per Cm.^{3}
Bide Arm gray, Newfoundland	93,500	601.0	1.96	14,730
Bide Arm gray, Newfoundland	86,300	566.0	1.92	13,470
Sops Arm breccia, Newfoundland	18,000	280.0	2.09	4,685
Sops Arm breccia, Newfoundland	13,900	269.0	2.28	4,412
Purbeck Cove, Newfoundland	38,000	466.0	2.38	10,050
Purbeck Cove (coarse)	4,280	126.0	1.93	1,414
High Street, Vermont	6,370	160.0	2.00	2,024
High Street, Vermont	6,090	156.0	1.99	1,949
Walker quarry, Vermont	2,690	99.0	1.91	988
Walker quarry, Vermont	3,340	112.0	1.94	1,193
Pittsford Valley, Vermont	2,730	114.0	2.19	1,217
Pittsford Valley, Vermont	2,540	97.0	1.93	963
Pittsford Valley, Vermont	2,550	97.0	1.92	955
Pittsford Valley, Vermont	2,410	98.0	1.98	967
Rutland "augen," Vermont	5,970	146.0	1.89	1,764
Rutland "matrix," Vermont	6,900	151.0	1.81	1,857
Rutland "average," Vermont	5,960	150.0	1.94	1,843
Rutland "Italian," Vermont	4,380	121.0	1.82	1,331
Rutland, Vermont	6,150	149.0	1.87	1,819
Rutland, Vermont	4,880	131.0	1.87	1,498
Rutland (?), Vermont	2,010	81.0	1.80	729
Danby "Imperial," Vermont	2,340	96.0	1.97	936
Danby "Metawee," Vermont	1,520	72.0	1.86	615
Colorado, Marble, Colorado	4,100	122.0	1.90	1,346
Colorado, Marble, Colorado	2,320	96.0	1.98	941
Colorado, Marble, Colorado	2,550	96.0	1.91	948
Colorado, Marble, Colorado	2,510	99.0	1.97	985
Silver gray, Tate, Georgia	79	16.5	1.84	67
Silver gray, Tate, Georgia	75	16.8	1.93	69

For the encouragement of that person who has made his first measurement, it should be pointed out that, for crystalline limestones at least, the irregularity coefficient is usually as regular as the degree of metamorphism apparent in the field. This statement can be verified by reference to determinations listed in Table 1, showing the range of coefficient for a number of specimens from a

single locality as well as range in variation with locality. Therefore, a small number of measurements are adequate to establish the irregularity coefficient for a region; subsequent determinations of length of contact can be made by grain count.

GRAIN COUNT AND ESTIMATING CONTACT LENGTH

The coefficient of irregularity (C), as used here, is defined as the length of contact per square centimeter (L) divided by the square root of the number of grains (G) per square centimeter, i.e.,

$$C = \frac{L}{\sqrt{G}}.$$

Its average value for the list of marbles in Table 1 is 1.96. This table has a preponderance of pre-tectonic marbles; if the number which has been recrystallized since deformation were given true representation, the average value for the irregularity coefficient would be near 1.85. The problem of pre-tectonic, para-tectonic, and post-tectonic development of the crystalline structure is not part of the subject under consideration. It is sufficient to indicate here that extremely detailed field and petrofabric studies at West Rutland show three ages for recrystallization to marble relative to the major deformative movements, and these are reflected in the irregularity coefficients. The Sops Arm marble is within 100 feet of a fault of several thousand feet displacement, and the tectonic influence appears in the high irregularity coefficient.

The average coefficient for Pittsford Valley marble is 2.0; it is higher in the dolomitic beds and diminishes in the slightly recrystallized pure calcite zones. The coefficient and the grain count can be used to estimate rapidly the length of contact between grains in marbles in near-by parts of the marble formation, as,

$$\frac{L}{\sqrt{G}} = C = 2.0.$$

If a marble in this group has a grain count of 2,500, its length of contact will be 100.

$$2.0 = \frac{L}{\sqrt{G}} = \frac{L}{\sqrt{2{,}500}} = \frac{L}{50},$$

$$L = 100.$$

USE OF LENGTH OF CONTACT

The length of contact in unit area may be used to estimate the following rock characteristics: (*a*) area of contact in unit volume, (*b*) average width of intergranular space, and (*c*) adsorptive capacity of the rock.

The area of contact (A) in unit volume is given approximately by the equation:

$$A = L^{3/2}.$$

This lies between an extreme high value $2L^{3/2}$ and an extreme low value $\frac{2}{3}L^{3/2}$. These are derived from area of grain-contact surfaces

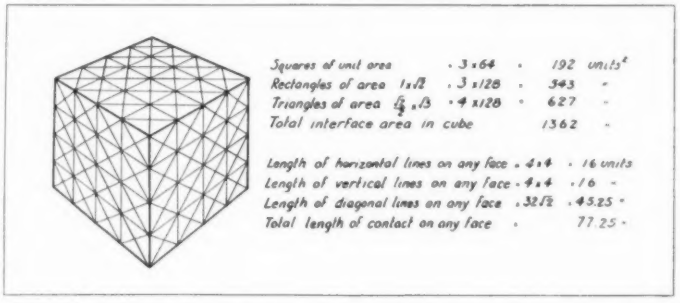
Squares of unit area . 3 x 64 . 192 units²
Rectangles of area 1 x √2 . 3 x 128 . 343 "
Triangles of area ½ x √3 . 4 x 128 . 627 "
Total interface area in cube 1362 "
Length of horizontal lines on any face . 4 x 4 . 16 units
Length of vertical lines on any face . 4 x 4 . 16 "
Length of diagonal lines on any face . 32√2 . 45.25 "
Total length of contact on any face . 77.25 "

FIG. 1.—Diagram of cube with surface at intersection of interfaces. The cube edge is 4 units long. The calculations at the right assume the presence of all possible interfaces using the lines on the cube face. Usually only half this number exist in a rock.

produced by shear of a cube to make the maximum number of shear surfaces. The extreme high value is calculated on the assumption that two shear planes of grain surfaces dip outward from each contact on any flat face (Fig. 1). The extreme low value is calculated

on the assumption that only one shear plane or grain surface dips outward from each contact on any flat face, although the shear planes for the cube as a unit have the same disposition (Fig. 2). The average value assumes that only one of two possible planes, and that the more favored one, will dip out from each contact in Figure 1.

In the first possibility the cube has almost 1,362 units of intergranular surface and 77.25 units of length of contact on any one

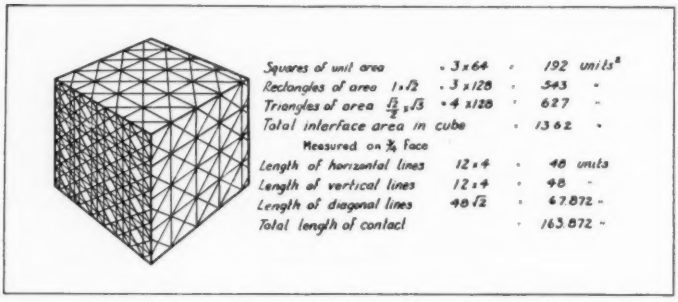
Squares of unit area . 3×64 . 192 units²
Rectangles of area 1×√2 . 3×128 . 543 "
Triangles of area $\frac{\sqrt{2}}{2}\times\sqrt{3}$. 4×128 . 627 "
Total interface area in cube . 1362 "
Measured on ¾ face
Length of horizontal lines 12×4 . 48 units
Length of vertical lines 12×4 . 48 "
Length of diagonal lines 48√2 . 67.872 "
Total length of contact . 163.872 "

FIG. 2.—Diagram of a cube with surface one-fourth distance from intersection of interfaces. The cube edge is 4 units long. The calculations at the right assume the presence of all possible interfaces using the lines on the cube face. Note that one plane only uses a line on this one-fourth distance-surface.

face. The area of intergranular surface calculated from the length of contact on any one face is 1,359, which approximates the real value very closely. The irregularity coefficient for this grain arrangement (2.41) is slightly higher than any measured in an actual rock and is approached only by the fine-grained marble from Purbeck Cove, Newfoundland (2.38).

The second possibility exists when the surface on which length of contact is measured is situated $\frac{1}{4}$ to $\frac{3}{4}$ of the distance between the intersecting vertical planes; this gives the finest grain and the greatest possible length of contact on the surface with no change in area of contact. This length of contact is 163.872 units. The calculated area of contact, 1,396, is $2\frac{1}{2}$ per cent above the observed value. The coefficient of grain irregularity shows a decrease to 2.23.

The third case assumes that each grain contact exposed on any surface is the result of only one of two possible emergent planes and not two, as was assumed in the first instance. The area of grain contact will be half as great, or only 681 units, as contrasted with 679.5 for the calculated value.

Usually one shear plane is dominant in the tectonite marbles, and it may even become a surface of translation; it is the *ab* plane of the structural petrologists. Therefore, the third formula is the one used on all *s* tectonite marbles and most others also. Both shear planes develop during deformation of many extremely elastic rocks, such as olivine-rich, igneous intrusives, and the second formula becomes applicable. Conditions that would render the first formula applicable have not been recognized, but they are possible and can be identified by the inclination of contact surfaces.

AVERAGE WIDTH OF INTERGRANULAR SPACE

The area of grain contact is also the area of one side of the intergranular spaces. The porosity or volume of intergranular space is the product of the area of grain contact and the available width. Part of the width is taken up by an adsorbed monolayer on either wall. The remaining space may be determined by exhausting the gas and measuring its volume. This volume divided by the area of grain contacts is the average width of the openings.

Width of space may vary widely in some rocks and be remarkably regular in others. In tectonite marbles pore width may be attributed to greater compressibility of calcite along the *c* axis than along the *a* axes. The spaces will be remarkably uniform if the calcite crystals are aligned almost parallel but will vary widely if they have heterogeneous arrangement. Just as compressibility coefficients determine regularity or irregularity in space width for metamorphic rocks, so coefficients of thermal expansion can become significant in igneous types. Width of space may be irregular or regular depending upon regularity or irregularity of crystal alignment in the rock.

ADSORPTIVE CAPACITY

Both walls of intergranular space are potential ground for adsorption from migrating solutions. The adsorbed molecules may then

react with the walls and initiate one step in metasomatic replacement. Amount of adsorption is a direct function of the area available, which is twice that for the intergranular space. Metasomatic deposits favor medium to fine-textured rocks. This may be attributed partly to lower diffusion distance from the center to the periphery of fine grains because distance varies as $G^{1/2}$. However, the absorption area varies as $2.828G^{3/4}$, and its effects would be modified correspondingly more than those of diffusion distance by like change in grain size. This may influence selective metasomatism significantly. It may be suggested that high adsorption and location of most metasomatic deposits in medium- to fine-textured rocks, even though coarse-textured types are more permeable, is correlative rather than coincidental.

VOLCANIC ROCKS OF THE WESTERN SAN AUGUSTIN PLAINS DISTRICT, NEW MEXICO

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ABSTRACT

Mountains surrounding the San Augustin plains in western New Mexico are composed of an extraordinary variety of volcanic rock types, including rhyolite, andesite, basalt, both silicic and basic tuff, and agglomerate. Correlation based on lithology indicates at least seventeen members in this volcanic series. The series probably is related to the Datil formation of Tertiary age described by Winchester in the Bear Mountains northeast of this area.

INTRODUCTION

A closed, intermontane basin known as the Plains of San Augustin lies in Catron County, western New Mexico (inset map, Fig. 1). The district is characterized by alluviated basins and somewhat tabular mountain masses of prevailingly flat-lying structure and thus has features in common with both the Colorado Plateau and the Basin and Range Province, to neither of which it can be assigned without qualification. The basin of a former lake (Lake San Augustin) lying in the western San Augustin plains has recently been described.[1] The geology of this part of New Mexico is virtually untreated in literature. For this reason it is believed that the studies described herein merit publication, although they were the result of reconnaissance incidental to the mapping of the lake basin. The region is within the area of Cibola National Forest map, and much of the district to be described is shown on the Pelona topographic quadrangle of the United States Geological Survey.

The western San Augustin plains are enclosed on the north by the Datil and Gallo mountains, on the west by the Tularosa Mountains and more subdued hills forming the Continental Divide, and on the south by the O-Bar-O, Pelona, and Luera mountains (Fig. 1). These mountains rise from 1,000 to 2,000 feet above the plains. The latter

[1] W. E. Powers, "Basin and Shore Features of the Extinct Lake San Augustin, New Mexico," *Jour. Geomorph.*, Vol. II (1939), pp. 345–56.

area declines to 6,775 feet in a *playa* at the west, and its margin largely approximates the highest shoreline of the former lake, 6,940 feet. The highest surrounding summits are Horse Mountain (9,450 feet) on the north, Black Mountain (8,625 feet) and the 9,415-foot summit in the Tularosa Mountains on the west, and O-Bar-O

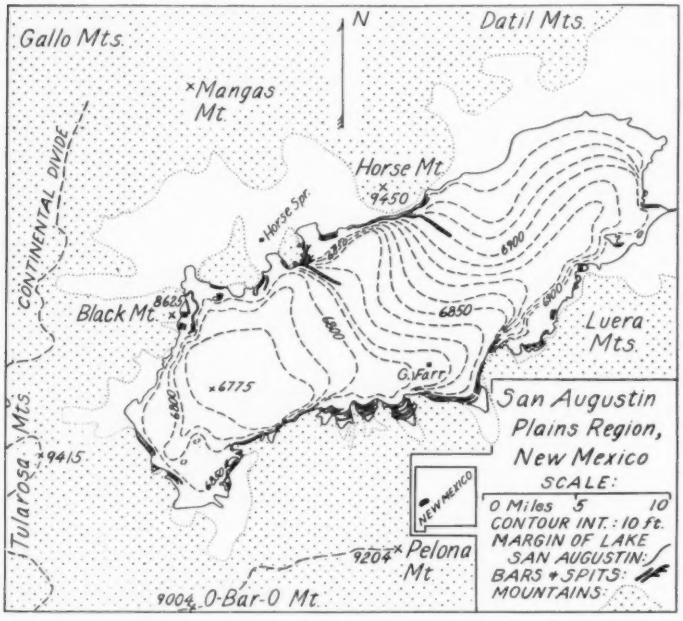

FIG. 1.—Map of San Augustin plains region, New Mexico, showing basin of extinct Lake San Augustin and the surrounding mountains.

Mountain (9,004 feet) and Pelona Mountain (9,204 feet) on the south. Groups of lower hills adjoin the lacustrine area between Horse and Black mountains and include a prominent conical summit known as Jack Peak (7,750 feet).

On the south, flattish, well-dissected spurs of Pelona Mountain extend to the margin of the plains and by their forms strongly suggest a dissected pediment surface surrounding the residual mass of Pelona Mountain. All of the mountain border is characterized by

mature or submature dissection, with no lakes and almost no streams. Foothills generally exhibit a tendency toward tabular outline and accordant summit level. These characters are related in part to their flat-lying structure but indicate also a former stage of pedimentation when the mountains stood lower with respect to baselevel.

Beyond the Continental Divide, west and south of San Augustin plains, drainage is to the Gila River. The plains themselves have interior drainage but would drain to the Rio Grande if the climate were humid. Semiaridity permits only such plants as greasewood, chico, sage, and a little short grass to grow in the plains. Timber line, here marking the lower limit of tree growth, stands at about 7,500 feet. Above that level scrubby junipers first appear, followed at somewhat higher altitudes by jack, pinon, and yellow pine.

SUCCESSION OF VOLCANIC ROCKS

The mountains of the San Augustin district are part of a great area of volcanic rocks in west-central New Mexico, information regarding which has been summarized by N. H. Darton.[2] Few portions of these volcanics have been studied, and none nearer to the San Augustin plains than the Mogollon district lying 40 miles to the southwest, and the north end of Bear Mountains, about 30 miles to the northeast. In the Mogollon district Ferguson found a series of Tertiary rhyolite flows separated by deposits of tuff and sandstone and flows of dacite, andesite, and basalt, the whole cut by numerous normal faults with throws not exceeding a few hundred feet.[3] In the northern Bear Mountains (Socorro County) D. E. Winchester found a thick series of lavas and associated deposits for which he proposed the name "Datil formation."[4] A section more than 1,800 feet thick included quartz rhyolite, rhyolite, andesite, tuff, and agglomerate, interbedded with and resting on sandstones, conglomerates,

[2] "Red Beds and Associated Formations in New Mexico," *U.S. Geol. Surv. Bull. 794* (1928), pp. 343–45.

[3] H. G. Ferguson, "The Mogollon District, New Mexico," *U.S. Geol. Surv. Bull. 715* (1921), pp. 174–88.

[4] "Geology of Alamosa Creek Valley, Socorro County, New Mexico," *U.S. Geol. Surv. Bull. 716* (1921), pp. 9–10.

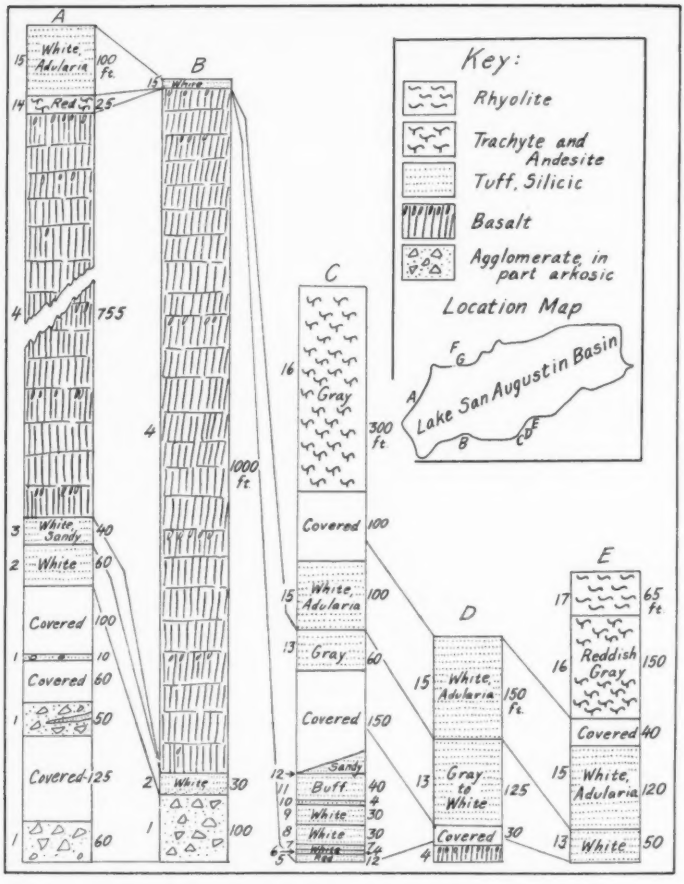

FIG. 2.—Representative columnar sections of volcanic rocks in the mountains surrounding San Augustin plains. Rock types identified by field inspection only. Figures at right of column denote thickness in feet; those at left, the sequence and a tentative correlation of the several members. Bases of sections lie at level of plains margin, at approximately the same altitude. Locations of sections: *A*, Black Mountain, Sec. 30, T. 5 S., R. 14 W.; *B*, Bat Cave, Sec. 20, T. 6 S., R. 13 W.; *C*, *D*, and *E*, about 3 miles east of George Farr or Crawford Ranch, in Secs. 12 and 1, T. 6 S., R. 12 W.

and clays. The volcanics in this section totaled only 799 feet. Winchester assigned a Tertiary age to his Datil formation.

The mountains surrounding the San Augustin Basin present a variety of volcanic-rock types. In the sections studied, little interbedding with sediments was observed. No criteria regarding age were discovered, but lithologic resemblances indicate a probable cor-

TABLE 1

SEC. A. BLACK MOUNTAIN (FOR LOCATION SEE FIG. 2)

Thickness in Feet	Lithologic Unit	Member as Numbered in Fig. 2
100.....	White rhyolitic tuff, with adularia. Weathers into platy fragments	15
25.....	Red, fine-grained andesite or trachyte, much white feldspar. Massively bedded. Possibly firmly indurated tuff	14
755.....	Basalt, in part coarsely porphyritic with plagioclase phenocrysts up to 1½ inches square. Vesicular in places. Not continuously exposed, and total number of flows undetermined	4
40.....	White tuff, very fine and sandy at top, with round concretions. No adularia feldspar	3
60.....	White tuff, firm and brittle, no adularia. Forms cliff	2
100.....	Covered	
10.....	Coarse, red arkosic tuff, with one pebble of white rhyolite or rhyolitic tuff	1
60.....	Covered	
50.....	Red arkosic tuff, ledge-forming, bearing very thin (2–3 inches) lense of white tuff	1
125.....	Covered	
60.....	Red, apparently water-laid, tuff, some cross bedding. Some layers contain partly rounded rock fragments. Arkosic	1
1,385		

relation with Winchester's Datil formation of Tertiary age. The following representative sections illustrate the diversity and irregular lateral distribution of the San Augustin volcanics. In Figure 2, 5 of these sections are plotted graphically with a tentative correlation of the various members. For convenience in comparing the sections members are numbered from 1 to 17. The most distinctive member was found to be No. 15—a compact rhyolitic tuff bearing abundant crystals of a glassy feldspar identified macroscopically as adularia. The identification of all rock types in these sections was made macroscopically in the field.

TABLE 2

SEC. B. BAT CAVE (FOR LOCATION SEE FIG. 2)

Thickness in Feet	Lithologic Unit	Member as Numbered in Fig. 2
Unknown..	Float indicates white rhyolitic tuff with adularia	15
1,000.....	Basalt, dense to vesicular, in part porphyritic with plagioclase laths	4
17.5...	White tuff, porous, weathers with small irregular lumps on surface	2
1.5...	Dense, compact white tuff	2
5.....	Soft, porous white tuff	2
6.....	Very fine-grained, prominently cross-bedded white tuff	2
100.....	Very coarse agglomerate with numerous large angular and partly rounded boulders, mainly of brown semivitreous trachyte and brown volcanic glass with feldspar phenocrysts, partly vesicular. Matrix of agglomerate is of fine tuffaceous material	1
1,130		

TABLE 3

SEC. C. NEAR GEORGE FARR RANCH (FOR LOCATION SEE FIG. 2)

Thickness in Feet	Lithologic Unit	Member as Numbered in Fig. 2
300.....	Gray trachyte, with flow structure. Makes cliff	16
100.....	Covered	
100.....	White rhyolitic tuff, with adularia and quartz grains	15
60.....	Gray tuff, with small flat lenses marking either flow lines or flat inclusions	13
150.....	Covered near fault, where section is measured, but $\frac{1}{4}$ mile to south Member 11 is directly overlain by 30 feet of fine, well-sorted and well-bedded tuff resembling gray sandstone	12
40.....	Buff, fine-grained tuff	11
4.....	Fine-grained white tuff, thinly bedded	10
30.....	White tuff bearing a few rock fragments	9
30.....	Massive white tuff	8
7.....	Nodular white tuff	7
4.....	White, fine-grained, water-laid tuff bearing concretionary masses of moss agate	6
12.....	Red to buff tuff bearing large rock fragments. Well bedded	5
837		

TABLE 4

SEC. D. NEAR GEORGE FARR RANCH (FOR LOCATION SEE FIG. 2)

Thickness in Feet	Lithologic Unit	Member as Numbered in Fig. 2
150.....	Dense white tuff, rings under hammer; rhyolitic and with adularia feldspar	15
125.....	Gray to white tuff; flat fragments give flowlike structure. Varies considerably in compactness. Basal part a breccia with basic fragments	13
30.....	Covered	
Unknown..	Vesicular basalt, coated abundantly with lime carbonate. Poorly exposed and total thickness unknown	4
305		

TABLE 5

SEC. E. NEAR GEORGE FARR RANCH (FOR LOCATION SEE FIG. 2)

Thickness in Feet	Lithologic Unit	Member as Numbered in Fig. 2
65.....	Gray rhyolite, compact, with flow structure	17
150.....	Dark reddish-gray trachyte or rhyolite, with flow structure	16
40.....	Covered	
120.....	White rhyolitic tuff, much quartz and adularia, soft and porous in upper part but so dense near base as to ring under hammer	15
50.....	White tuff, many flat fragments, porous, weathers to form cavernous surface	13
425		

TABLE 6

SEC. F. MOUNTAIN 1 MILE SOUTHWEST OF OLD HORSE SPRINGS, IN SEC. 36 T. 4 S., R. 14 W., PELONA QUADRANGLE (LOCATION INDICATED IN FIG. 2)

Thickness in Feet	Lithologic Unit
455	White tuff, containing pebbles of andesite and quartz monzonite. Weathers into great cliffy masses. Cut by small olivine diabase dike, 3–5 feet in thickness
10	Covered
15	White tuff, much feldspar. Pebbles of monzonite
30	Covered
25	White rhyolitic tuff, brittle and dense in part
35	Covered
50	Porous, massive tuff, pink at bottom and white at top
75	Covered
20	Red, pebbly arkosic tuff
715	

TABLE 7

SEC. G. ABOUT 3 MILES EAST OF TUT RANCH, IN SEC. 12, T. 5 S. R. 14 W. PELONA QUADRANGLE (LOCATION INDICATED IN FIG. 2)

Thickness in Feet	Lithologic Unit
150	Vesicular basalt, plagioclase phenocrysts
50	Pinkish rhyolite with much biotite and little quartz
250	Basalt, vesicular in part and with plagioclase laths up to 1 inch long. Vesicular zones seem to indicate that only two flows are present
50	White porous tuff, with fragments of gray lava
40	Porphyritic basalt with large plagioclase laths, vesicular at top
540	

Certain of these volcanic rocks are shown in Figures 3–5. Figure 3 shows Bat Cave, a shallow, nichelike opening in the mountain front where Section *B* was measured. The cave has an arched entry about 75 feet in height and is less than 100 feet in length. The cave was eroded largely by wave action in Lake San Augustin, in the agglomerate listed as Member 1 in Section *B*. Member 2, white tuff, is exposed prominently on the left (east) but thins and nearly pinches out above the cave entry. The cliffs above are composed of the thick series of basalt flows forming Member 4 in the section. The floor of Bat Cave is about 100 feet above the level of the *playa*, from which Figure 3 was photographed.

FIG. 3.—Bat Cave, in cliff of volcanic rock forming southeast margin of *playa* area. Compare with Sec. *B* in Fig. 2.

Figure 4 shows Member 8 with its characteristic cliffy outcrop and cavernous weathering surface, overlain by the somewhat darker Member 9. Figure 5 shows Member 6, a fine-grained, water-laid tuff bearing concretions of moss agate, resting on the darker agglomerate of Member 5.

The correlation of these members as suggested in Figure 2 is based wholly on lithologic resemblances and sequence and should be regarded as tentative until confirmed by detailed field and petrographic study. Sections *F* and *G* did not fit readily into the sequence. The presence of the basic dike in Section *F* may indicate that this section belongs to the earlier part of the eruptive period.

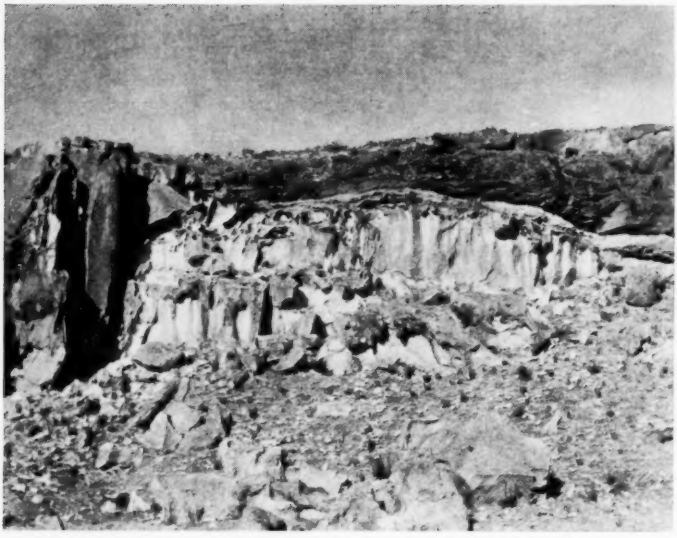

FIG. 4.—Cavernous surface of weathering characteristic of white tuff forming Member 8, near base of Sec. *C*, Fig. 2.

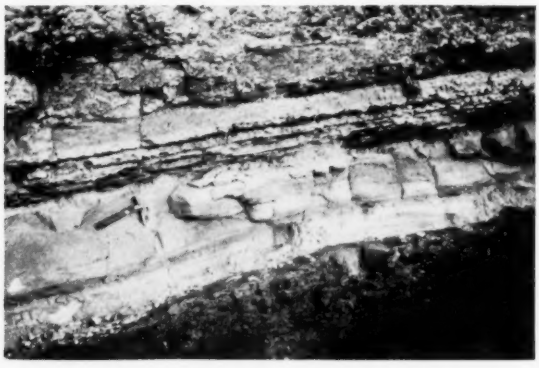

FIG. 5.—Fine-grained, white, water-laid tuff, containing nodules of moss agate. Red agglomeratic tuff below. These are Members 5 and 6 of Sec. *C*, Fig. 2.

STRUCTURE

These volcanics are mainly horizontal or nearly so. Dips of a few degrees are present at places—particularly in Sections *C* and *F* of those described. Topography and a few observed faults not exceeding 80 feet in throw indicate that the various units of the mountain border are separated by faults in a mosaic pattern, but structural relations are largely concealed by detritus. The configuration of San Augustin Basin and its relation to its pedimented mountain borders strongly suggest that the basin itself is a fault trough. However, compelling evidence for this remains to be worked out.

ACKNOWLEDGMENTS.—Field work on which this paper is based was carried out in 1932 and 1934 under a grant from Northwestern University. The writer acknowledges with pleasure the aid given by Mr. I. P. Schwade, field assistant, and Professor C. E. Needham, of New Mexico School of Mines, who gave valuable advice in the field and aided in measuring some of the sections.

REVIEWS

The Geology of China. By J. S. Lee. London: Thomas Murby & Co., 1939. Pp. 528; figs. 93. $9.00.

This volume of over five hundred pages is a compact but comprehensive summary of the geology of half a continent as far as it is known. The facts are stated clearly and in convenient form. A highly speculative theory of continental folding and movement is developed. The substance of the volume was delivered by the author in a series of lectures at British universities in 1934–35 and has since been expanded to a well-rounded presentation. Two things are necessary to an understanding of it—a knowledge of the geography of China and ability to keep in mind the geologic connotations of Chinese names. The geographical need is in a measure supplied by the opening chapter on the "Natural Provinces of China," with an outline map. Stratigraphy is treated in the following 140 pages under the heads of the "Ancient Floor," "Paleozoic Transgressions," and "Post-Paleozoic Formations." Descriptions of formations and their distribution are accompanied by lists and illustrations of type fossils, ranging in age from the pre-Cambrian *Collenia cylindrica* Gr. to early man, *Sinanthropus pekingensis*. The subject of regional stratigraphy is restated formation by formation, in systematic order from top to bottom of each section for each region with lithologic descriptions and lists of key fossils. The descriptions, though brief, are quite adequate for recognition of the local facies, and the arrangement is in very convenient form.

The Paleozoic, Mesozoic, and Neozoic sediments were deposited over subsiding areas, which are discussed as "geosynclines." Grabau, whose contributions to the geology of China command the highest respect, compares the depressions to the Appalachian geosyncline and has given them the name of "Cathay." Thus Lee describes the Paleocathaysian, Mesocathaysian, and Neocathaysian geosynclines. The submerged areas are illustrated by four paleogeographic maps, delineating the seas of Sinian, Ordovician, Devonian, and Triassic times. It must be said that they appear to represent basins rather than troughs. Nevertheless, it is perhaps not misleading to describe them and the intervening lands as geosynclines and geanticlines, that is, as "flexures of low angle and of great breadth, both upward and downward."[1] This definition does not exclude—indeed,

[1] J. D. Dana, *Manual of Geology* (Philadelphia: T. Bliss & Co., 1895), p. 106.

it may suggest—that Dana had in mind the effect of subsidence and uplift due to vertical forces; but if we substitute the term "fold" for "flexure," we may convey the idea of horizontal compression. This the author of *The Geology of China* clearly states as his concept, saying:

> If a geosyncline is a symmetrical trough, as implied in E. Haug's interpretation, then we might consider such a depression as resulting from mere subsidence due to the simple operation of gravity. Since the geosynclines under consideration are asymmetrical, application of lateral pressure is thereby suggested. This, together with the detailed tectonic evidence afforded by the Great Kingan, the eastern flank of the Tai-hang, and parts of the Kweichow Plateau, leads us to conclude that the Cathaysian geosynclines and geanticlines are a group of compressive features due to pressure from the northwest and a powerful resistance on the southeast [p. 244].

Again he writes:

> Reasons have been given to show that these grand synclinoria and anticlinoria cannot be regarded as features resulting merely from vertical subsidence and uplifting, but were brought about by lateral pressure. They are gigantic folds involving possibly the whole thickness of the continental mass. It is quite obvious that the pressure was exerted by the continent toward the Pacific or vice-versa [p. 329].

It would hardly be worth while to cite these conclusions if it were not that they form the basis for the author's discussion of the continental structure.

Appreciating the significance of mechanical principles in the interpretation of structure, the author devotes a chapter to "Shear-forms"—that is, to the types which result from shearing. He distinguishes three types and designates them by Greek letters. The first comprises the effects of compression and tension resulting from simple shear—the minor folds and faults which are commonly illustrated by the strain ellipsoid, were discussed by Becker in 1896, and are familiar to students who use Leith's *Structural Geology*. The other two "types" are more or less complicated effects of a twisting movement (rotation) combined with pressure and shearing. The author illustrates them by reproducing the folds developed in wet paper on a soft base by pressing and turning as with the thumb. The method is one that originated with S. Tokuda, a Japanese geologist. It serves in any given case to show how a particular structure may have been produced, but inferences from the experiment are no stronger than the assumption that the rice paper behaves as the earth's crust has. Since the author makes no reference to the work of Becker, Leith, or Tokuda, it may be thought that he did not know of it.

The "shear-forms" constitute the basis of a speculation as to the conditions under which the Cathaysian geosynclines were produced. Since the axes of these supposed folds run northeast-southwest, they may be attributed to the action of a shearing couple oriented in a general north-south direction. This idea the author develops as follows:

From the study of the structural details of the Cathaysian area we have found that the region is covered by the first "type of shear-form." [The author uses a Greek letter instead of "first."—REVIEWER.] The orientation of this shear-form forces us to the conclusion that the Cathaysian region has been subjected to compression perpendicular to the continental border, and that this compression has been induced by a southerly movement of the continental mass against the Pacific floor, or by the latter moving northwards against the continent. Here we are up against the difficulty of making our choice. No choice can be made at the present stage. What we do know, however, is the fact that relative north-south movements have taken place intermittently between the eastern Asiatic continent and the Pacific floor since Sinian times.

This important conclusion rests upon the assumption that the geosynclines are due to horizontal pressure, not to vertical subsidence, and that the pressure was necessarily developed by rotational shear between the continental and oceanic masses. Neither assumption is compelling. In this work, however, they lead to a discussion of "Facial Traits of the Earth and Their Dynamic Significance," in which the writer extends the inference to the mountain ranges of the entire northern hemisphere, illustrating his idea by photographs of the globe upon which he has sketched the structural pattern.

Impelled to further speculation, the author proceeds as follows, under the heading "Origin of Tectonic Movements and Marine Transgressions":

Thus far our argument is straightforward. The whole logical structure will either have to stand or fall with the basic conception of tectonic types and their mechanism, as we understand it. Let us now go a step further with the assumption that our interpretation of the tectonic types outside eastern Asia is not far wrong and that our deduction holds. There are not many sources of force which could produce the kind of movement arrived at in the course of our argument.

The harmonic zones upon which emphasis has been laid suggest that their origin is due either to tidal force or to changed rotation of the globe. Convincing physical arguments are decidedly against the tidal force alone as an adequate cause of continental movements. Let us then turn to rotational force. If the earth has been rotating at a constant speed since the early time of its existence, it would have established long ago the required ellipticity; and the resultant of the centrifugal force and gravity would have no horizontal component to satisfy

our requirement. If, on the other hand, a change of speed occurred periodically, a surface readjustment would necessarily follow, unless the interior of the earth is utterly devoid of strength.

Unwilling to rest his argument on the unknown strength or weakness of the earth's interior, the writer tested the deformation of a soft layer spread upon the concave surface of a hollow sphere, which was rapidly rotated, and obtained folds similar to the several types he had found on continental margins. It now becomes necessary to find an adequate cause of variability in the speed of rotation of the earth, and this is discovered in the suggestion that "condensation of mass" has resulted from "deep-seated gravitational differentiation taking place on an extensive scale in the interior of the earth." Marine transgressions are next considered, and a graphic representation of important tectonic movements and extensive marine transgressions throughout geologic time is offered. Recognizing that the attempt to analyze earth movements on this "incomplete" evidence is somewhat "hazardous" the author concludes nevertheless:

> A certain outstanding time-relation between the sweeping transgression and revolutionary movements that ensued is revealed in a striking manner. The data thus assembled, when correlated with the "pulsations" of A. W. Grabau, who vigorously advocates universal transgression and regression for a given geological period, seem to favor the conclusion that it is the continued contraction of the earth that has caused the increase of its rotational speed.

Throughout the speculative discussion of tectonic types and their origin there is evidence in the text and in the bibliography attached to the chapter of the influence of ideas of world-wide periodicity as advocated by Stille, of general rather than local causes and diastrophic movements, and of continental drift.

The book closes with a chapter on Pleistocene climate and the one hundred pages devoted to the "Regional Stratigraphy," already mentioned. The work is clearly written, and each chapter is followed by a pertinent, selected bibliography. Students of the geology of China will find the assembly of facts a most useful compendium.

BAILEY WILLIS

O. C. Marsh, Pioneer in Paleontology. By CHARLES SCHUCHERT and CLARA MAE LEVENE. New Haven, Conn.: Yale University Press, 1940. Pp. xx+541; pls. xxx; figs. 33. $5.00.

Of the three great founders of vertebrate paleontology in America—Leidy, Cope, and Marsh—the first two have received adequate biographi-

cal treatment. In the volume before us justice is at last done to the accomplishments of O. C. Marsh, third of this illustrious trio. The biography is scholarly and well documented but withal eminently readable.

Apart from its purely biographical sections, the book is a mine of interesting data for the paleontologist. The accounts of Marsh's expeditions with student assistants give graphic and amusing stories of the opening up of famous fossil fields. In later years professional collectors were employed. A chapter is devoted to these men who ranged in character from wild and wooly westerners like "Sam Smith of the Rocky Mountains" to such a potentially eminent scientist as the late S. W. Williston. A special section is devoted to the story of John Bell Hatcher, justly termed "king of collectors," whose name looms as large in the folklore of vertebrate paleontologists as does that of Paul Bunyan among lumberjacks. Still another chapter gives an account of Marsh's laboratory assistants, who included many men who later rendered important contributions of their own to paleontology.

Four chapters are devoted to a summary of Marsh's scientific discoveries. It is interesting to compare the field of Marsh's work with that of his rival Cope and note the former's unerring instinct for showmanship. Both wrote extensively on mammals, but Marsh emphasized the massive and grotesque uintatheres and titanotheres and the dramatic evolutionary story of the horses. Among lower vertebrates Cope excelled in fishes, amphibians, and primitive reptiles—scientifically important but with little popular appeal—while Marsh concentrated on the spectacular dinosaurs and toothed birds.

Marsh's ability developed late. He seems to have been an "average" youngster, fond of hunting and fishing and not too fond of learning or labor. It was not until he was twenty-one—and still far down in "prep school"—that ambition began to stir, and he determined to follow a scientific career. He was twenty-nine before he graduated from college. In 1866, after some years of postgraduate study at home and in Germany, he received a professorship at Yale; but even up to 1870, when Marsh was nearly forty years of age, his publications in vertebrate paleontology were few in number, brief, and for the most part of little consequence.

Much of this "lag" may have been due to the fact that paleontology was not his first love. His early interests had been in mineralogy, and his training aimed in that direction. If, however, he wished a post at Yale, it was paleontology or nothing—so paleontology it was. Parenthetically, it is highly probable that the deficiency in his morphological background was the reason for his reliance upon scientific assistants in his later work.

Once Marsh began to show interest in scholarly pursuits, he received strong backing from his uncle, George Peabody, famous and wealthy businessman and philanthropist. Peabody financed Marsh's undergraduate and graduate studies, made him independently wealthy, so that he was able to accept an unsalaried professorship, and founded, through Marsh and mainly for his benefit, the famous Peabody Museum at Yale. Even without his assistance Marsh, with his energy and ambition, might have been a success; but his path would have been a thornier one.

In strong contrast with Marsh's slow beginnings were the achievements of the seventies. During this decade he published more than one hundred papers on his new discoveries in the West, many of them of fundamental importance. The evolution controversy was at its height; his fossil finds furnished strong ammunition for the theory's protagonists, and he himself made a notable address on the subject in 1877.

During this period Marsh's scientific reputation became firmly established, and honors began to flow his way. In 1879 he was president of the A.A.A.S.; in 1874 he was elected to the National Academy, and shortly became its acting president and began a twelve-year term as president in 1883. In 1882 he was appointed vertebrate paleontologist of the United States Geological Survey, newly organized and with friends of Marsh in control; this appointment brought vast amounts of new material to him.

But with growing fame Marsh's scientific work began to decline. This situation seems to have been due in part to his having turned in great measure to social and administrative occupations and partly to inability to digest the plethora of accumulating fossils. In the closing years of his life his fortunes were on the wane. In 1890 the smoldering feud with Cope burst into a violent flame which badly singed both parties. In 1892 government support was withdrawn, at a time when his personal fortune had largely disappeared, and left him relatively impoverished.

Marsh's character was an interesting one. As our authors freely admit, he had his faults—many of them. He was taciturn, secretive, autocratic, suspicious, jealous, niggardly toward his employees, a procrastinator in his later years, a seeker of praise and of the society of the rich and powerful. Many of these traits were highly irritating to his scientific assistants and contemporaries and led to the development of violent prejudices against him on the part of many vertebrate paleontologists.

Four decades, however, have passed since his death, and we can now take a more dispassionate view, more justly appraise his contributions. With all his faults, Marsh looms up as a powerful and impressive figure—strong, cool, determined, and disciplined, with an excellent brain and a pas-

sion for scientific discovery. Through his energy there was accumulated in New Haven one of the most important collections of fossil vertebrates ever made. And out of his laboratory, for a quarter of a century, came a steady stream of important scientific discoveries. His will ever be an important name in the annals of paleontology.

A. S. ROMER

Earthquakes and Other Earth Movements. By JOHN MILNE. Revised and re-written by A. W. LEE. Philadelphia: P. Blakiston's Son & Co., 1939. Pp. 244; figs. 83. $3.50.

Earthquakes and Other Earth Movements, by the pioneer seismologist, John Milne, appeared first in 1883 and, as the standard work on the subject, had passed through six editions before the author's death in 1913. Since that time certain phases of seismology have developed so strongly that recently Dr. A. W. Lee welcomed an invitation to bring this important work up to date. He has followed the general outline adopted by Milne as closely as possible, though it was necessary to re-write completely the portion dealing with instrumental seismology and its applications and to revise extensively most of the other parts of the book. The outcome is a very readable volume covering the subject in an authoritative way.

The first fifty pages describe in clear and interesting fashion the observed earthquake phenomena and their various effects on land, in bodies of water, and on human constructions. The succeeding four chapters on seismographs, elastic waves in solids, records of earthquakes, and their analysis give the reader an excellent understanding of these subjects by means of a skilful explanatory treatment which avoids, as far as possible, confusing technicalities.

Among the newer material, the factual information and discussion of deep-focus earthquakes and particularly the chapter "Anaseisms and Kataseisms" will be especially helpful to the geologist somewhat familiar with seismology. The chapter on the "Mechanism of Earthquakes" is not so strong. Seismic methods of prospecting are among other topics treated.

R. T. C.